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Electro Scientific Industries

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STANDARDS

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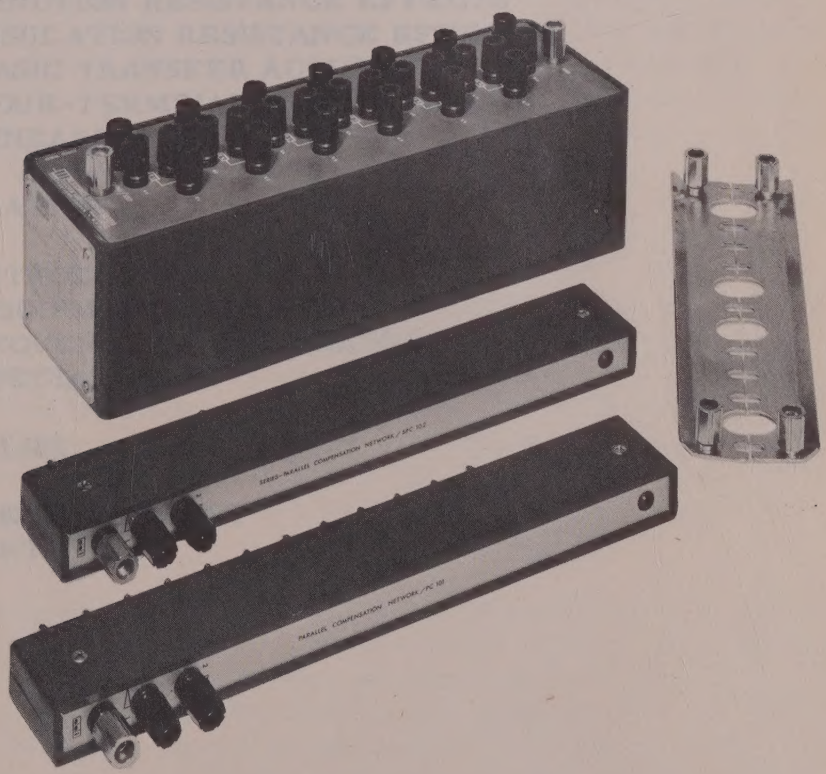
MODEL

SR 1010

Instruction Manual

RESISTANCE TRANSFER STANDARD

ELECTRIC SHOP
DEPT. 119-E.



ELECTRIC SHOP
DEPT. 119-E.

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SECTION I

DESCRIPTION AND SPECIFICATIONS

1.1 DESCRIPTION

Each MODEL SR 1010 RESISTANCE TRANSFER STANDARD is a resistance box containing twelve nominally equal precision resistors. SR 1010 boxes are available in various resistance values.

There are three basic ways of using a Model SR 1010, depending upon the accuracy required. In many applications, the resistor adjustment accuracy is high enough that the resistors can be assumed to have exactly their nominal values. For higher accuracy, certified calibration data can be used to correct the resistance values. For the ultimate accuracy in a laboratory having a high-accuracy one ohm reference standard, a set of SR 1010 boxes can be used to transfer calibration from the one ohm reference to the entire chain of resistance measuring equipment and standards in the laboratory with an accuracy at the time of calibration much better than the long-term accuracy to which any of the equipment could be certified.

Each MODEL SR 1010 RESISTANCE TRANSFER STANDARD has a calibration chart attached to it, giving the measured deviation of each resistor from its nominal value. The chart also includes the calculated average deviations of resistor groups for use in series, parallel and series-parallel groups. The ESI calibration data supplied is directly traceable to standards certified by the National Bureau of Standards. Blank calibration charts are available for subsequent calibrations. The excellent stability and unusually low temperature coefficient of the resistors used in the SR 1010 assure the maintenance of high accuracy between calibration periods and over normal temperature ranges.

The design of the MODEL SR 1010 RESISTANCE TRANSFER STANDARD and its accessories facilitates the transfer of resistance calibration from one resistance level to another. The series, parallel and series-parallel connections of resistor groups in an SR 1010 to give resistance values of 0.1, 1 and 10 times the individual resistor value is particularly useful in calibrating a set of SR 1010's to a short-term accuracy much better than any long-term certification. A laboratory having one or more Thomas-pattern one ohm resistors as its reference standard can use a set of SR 1010 boxes to calibrate measurements over a wide resistance range to very nearly the same accuracy as that of its one ohm reference standard.

The resistors in an SR 1010 are permanently connected in series. The provision of two binding post terminals at each junction allows accurate four-terminal measurement of any resistor or series group of resistors. Accessories are available for parallel and series-parallel connections. A pair of shorting bars, ESI Model SB 103, is used to connect any number of resistors in parallel or a group of nine resistors in series-parallel. Two different compensation networks, ESI Models PC 101 and SPC 102, are used to eliminate loss of accuracy at the lower resistance levels in making four-terminal measurements of ten resistors in parallel and nine resistors in series-parallel. As a result of the special design of the four-terminal junctions between binding posts and resistors, and the use of the parallel and series-parallel compensation networks, the actual values of four-terminal series, parallel and series-parallel resistor groups will agree with their values calculated from individual resistor values to better than ±0.1 microhm.

The SR 1010 owes its high accuracy and stability to the precision resistors used. The resistors are unifilar-wound on specially processed mica cards, and use a modern alloy resistance wire which has excellent stability, extremely low temperature coefficient and negligible thermal emf to copper. All the resistors in an SR 1010 are wound from the same spool of wire in order to yield the best temperature coefficient and stability matching between resistors. Each resistor is carefully built and inspected to insure maximum control of quality. Resistors for use in Model SR 1010's are selected for minimum temperature coefficient and given a rigorous accelerated aging treatment. The complete resistance transfer standard is given additional stabilization treatment, followed by an extended series of tests to ensure that every SR 1010 conforms to the highest standards of quality.

1.2 SPECIFICATIONS

MODEL SR 1010

RESISTANCE VALUES: Twelve equal four-terminal resistors connected in series. Standard Values: 1, 10 or 100 ohms; 1, 10 or 100 kilohms per step. Values required for 242A system calibration: 10 ohms, 1 kilohm, 100 kilohms.

CALIBRATION TRANSFER ACCURACY WITH PARALLELING COMPENSATION NETWORK: 100 to 1 transfer
±(1 ppm + 0.1 microhm at parallel value)
10 to 1 transfer
±(1 ppm + 1 microhm at series-parallel value)

INITIAL CALIBRATION CHART ACCURACY: ±10 ppm (traceable to National Bureau of Standards)

INITIAL ADJUSTMENT ACCURACY OF RESISTORS: ±20 ppm, matched within 10 ppm

LONG-TERM STABILITY OF RESISTORS: Resistance will remain within ±50 ppm of nominal value for more than one year.

CALIBRATION CONDITIONS: 23°C, four-terminal resistance measurements

TEMPERATURE COEFFICIENT OF RESISTORS:

100 ohms and higher, ±5 ppm/°C, matched within 3 ppm/°C
10 ohms and lower, ±15 ppm/°C, matched within 5 ppm/°C

POWER COEFFICIENT OF RESISTORS FOR TYPICAL MEASUREMENT DUTY CYCLE:

100 ohms and higher, ±0.1 ppm/mw/resistor
10 ohms and lower, ±0.3 ppm/mw/resistor

POWER RATING: 1 watt per step or 5 watts distributed over ten resistors

BREAKDOWN VOLTAGE: 1500 volts peak to case

DIMENSIONS: 12.2" long, 4.4" wide, 4" deep.

WEIGHT: 3-1/4 lbs. net

STANDARD SR 1010 VALUES:
PER STEP

(R) Value - Per Step		1Ω	10Ω	100Ω	1k	10k	100k
One Resistor Alone	Maximum Milliamperes	1000	320	100	32	10	3.2
	Maximum Volts	1	3.2	10	32	100	320
10 Resistors in Parallel (R/10)	Maximum Milliamperes	7100	2300	710	230	71	23
	Maximum Volts	0.71	2.3	7.1	23	71	230
10 Resistors in Series (10R)	Maximum Milliamperes	710	230	71	23	7.1	2.3
	Maximum Volts	7.1	23	71	230	710	2300*

*Do not exceed 1500 peak volts to case

MODEL SB 103 SHORTING BARS

FUNCTION: A pair of shorting bars used to connect any number of resistors of a MODEL SR 1010 RESISTANCE TRANSFER STANDARD in parallel or nine of its resistors in a series-parallel arrangement.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTANCE: End to end: approximately 100μ ohms/bar.

MAXIMUM CURRENT: 10 amps/bar

MODEL PC 101 PARALLEL COMPENSATION NETWORK

FUNCTION: Used in addition to an SB 103 pair for the four-terminal parallel connection of ten resistors in an SR 1010 to yield the same resistance as the value calculated from individual four-terminal resistor measurements.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTOR MATCHING: Matched to ±0.05%

MAXIMUM CURRENT: 2 amps

BREAKDOWN VOLTAGE: 1500 volts to case

MODEL SPC 102 SERIES-PARALLEL COMPENSATION NETWORK

FUNCTION: Used in addition to an SB 103 pair for the four-terminal series-parallel connection of nine resistors in an SR 1010, to yield the same resistance as the value calculated from individual four-terminal resistor measurements.

EFFECTIVE RESISTANCE AND ACCURACY: See COMBINED FUNCTIONAL SPECIFICATIONS.

RESISTOR MATCHING: Matched to ±0.05%

MAXIMUM CURRENT: 2.0 amps

BREAKDOWN VOLTAGE: 1500 volts to case

COMBINED FUNCTIONAL SPECIFICATIONS:

Resistor grouping	Ten resistors in parallel	Nine resistors in series-parallel	Ten resistors in series
Nominal value (relative to individual resistor value R)	0.1R	R	10R
Four-terminal measurement	Resistance added to value calculated from individual resistor values (value and tolerance in microhms)		
With SB 103 and PC 101 or SPC 102	0±0.1	0±1	
With SB 103 alone	50±10	200±40	
With no accessories			0±10
Two-terminal measurement			
With SB 103	150±30	300±60	
With no accessories			300±60

SECTION II

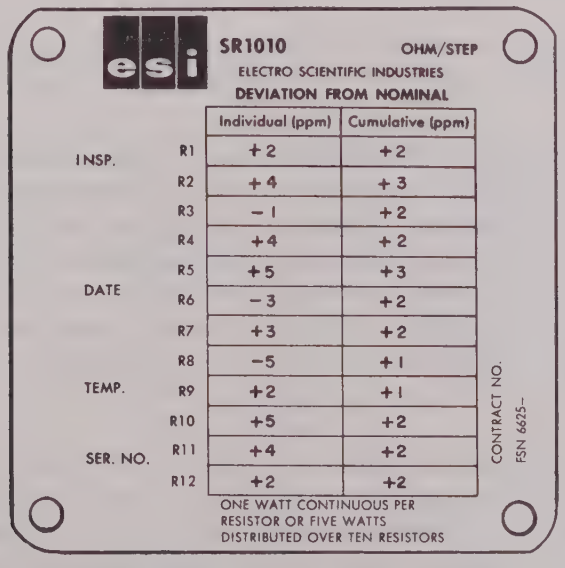
OPERATING INSTRUCTIONS

2.1 BASIC OPERATIONS

2.1.1 USING THE CALIBRATION CHART

The calibration chart on the end of each SR 1010 gives resistance calibration data for individual resistors and groups of resistors in the SR 1010, in terms of their deviation from nominal value, expressed in parts per million. These values are based on four-terminal measurements; two-terminal measurements must be corrected for the connection resistances listed in the specifications and discussed in Section 2.2 (Connections).

A sample calibration chart is shown in Figure 2.2.1.



	Individual (ppm)	Cumulative (ppm)
R1	+2	+2
R2	+4	+3
R3	−1	+2
R4	+4	+2
R5	+5	+3
R6	−3	+2
R7	+3	+2
R8	−5	+1
R9	+2	+1
R10	+5	+2
R11	+4	+2
R12	+2	+2

FIG. 2.2.1

The first column gives the measured deviation of each resistor from its nominal value. The second column gives the cumulative average of the deviation figures in the first column, rounded to the same number of significant figures as the first column. For example, to the right of R7, the figure in the first column is the measured deviation of R7 from nominal, while the figure in the second column is the calculated average deviation of resistors R1 through R7.

The cumulative average deviation in the second column calibrates any series, parallel or series-parallel connection of the corresponding group of resistors in which the power divides equally among all the resistors in the group. For example, the first nine resistors in a one ohm per step box can be connected in series for a nominal value of nine ohms, in parallel for one-ninth of an ohm, or in series-parallel for one ohm; the actual value of each of these three alternate connections will be exactly the same number of parts per million away from the nominal value for that connection.

The calibration chart data supplied initially with each SR 1010 is traceable to the National Bureau of Standard with the specified accuracy under the stated laboratory environmental conditions. A set of SR 1010's can be easily recalibrated relative to any one ohm reference standard, using the procedures described in Section IV.

2.1.2 HIGH-ACCURACY TRACEABLE RESISTANCE MEASUREMENTS

In precision resistance measurement, the calibration of any resistor must be traceable through a succession of precise resistance comparisons to a certified reference standard for the unit of resistance. At the present state of the art, the highest-accuracy type of resistance reference standard is the Thomas pattern one ohm resistor. These resistors are certified by the National Bureau of Standards to an accuracy of ±2 parts per million after the stability of the particular resistor has been demonstrated.

Standards presently available at other resistance values cannot be certified to as high an accuracy, since they are typically somewhat less constant in resistance than the one ohm Thomas pattern over extended periods of time, or when subjected to environmental changes or mechanical shock. The short-term stability of a precision resistor in a laboratory environment, however, is typically much better than its long-term calibration accuracy. The accuracy of a calibration

certificate must reflect this possible long-term instability, but a fresh calibration at the time of use may be far more accurate. Thus the laboratory equipped to trace all of its measurements to one ohm reference standards can calibrate its entire chain of resistance measuring equipment and resistance standards over a wide range of values to a short-term calibration accuracy much better than the accuracy to which such equipment could be certified for use over a long period of time or after transportation from one laboratory to another.

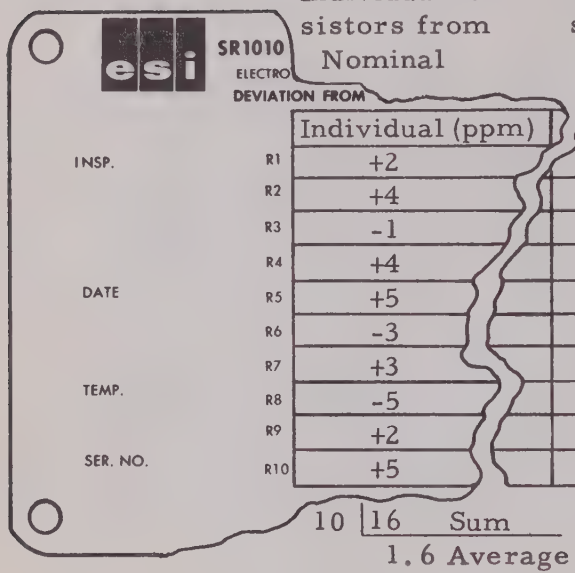
A set of SR 1010 boxes is particularly useful for such high-accuracy calibration, since the SR 1010 is particularly designed for the transfer of calibration from one resistance level to another. This is accomplished by calibrating an SR 1010 at one resistance level and then reconnecting its resistors to yield a different resistance value known to the same accuracy. The comparisons at each resistance level can be made at a one-to-one resistance ratio, ensuring maximum accuracy. Thus the only certified resistance standards which a laboratory needs to maintain are its one ohm reference standards. The traceable calibration of other standards over a wide range of resistance values can be accomplished through the use of a set of SR 1010 RESISTANCE TRANSFER STANDARDS and a one-to-one Kelvin comparison bridge or double ratio set, yielding a higher accuracy than could be obtained by shipping the other standards to the National Bureau of Standards for certification.

The procedures for the complete calibration of a set of SR 1010's from a one ohm reference standard is described in detail in Section IV. For the absolute maximum of accuracy in any specific calibration, those parts of the calibration procedure required for that application should be incorporated as an integral part of the operating procedure at the time of use, in order to hold resistance changes with time or ambient conditions to an absolute minimum. These calibration transfer procedures for the more common applications are described in Section 2.3.

2.1.3 DIVIDER CALIBRATION

To make precision linearity measurements of a voltage divider it is necessary to first calibrate a standard voltage divider. Due to its excellent short term stability and its four-terminal construction which makes it simple to calibrate, the ESI MODEL SR 1010 is ideal for use as such a standard voltage divider.

The following outlines the procedure for calibrating the SR 1010 as a voltage divider with ten equal steps, using the data given on its calibration chart. If the calibration chart has not been verified recently refer to Section 4.3.3 (Calibration of Individual Resistors).



	A Deviation of Individual Resistors from Nominal	B Deviation of Individual Resistors from Average (ppm)	C Cumulative Sum of B (ppm)	D Linearity Deviation at Tap (ppm)
	Individual (ppm)		0.0	0.0
R1	+2	+0.4	+0.4	+0.0
R2	+4	+2.4	+2.8	+0.3
R3	-1	-2.6	+0.2	+0.0
R4	+4	+2.4	+2.6	+0.3
R5	+5	+3.4	+6.0	+0.6
R6	-3	-4.6	+1.4	+0.1
R7	+3	+1.4	+2.8	+0.3
R8	-5	-6.6	-3.8	-0.4
R9	+2	+0.4	-3.4	-0.3
R10	+5	+3.4	0.0	0.0

10 | 16 Sum

1.6 Average

FIG. 2.1.3

1) Add up the deviations from nominal of the first ten resistors of the SR 1010.

These are the values given in the first column of the calibration chart on the end of the SR 1010, see Figure 2.1.3 column A.

2) Divide this sum by ten to find the average deviation.

3) Subtract the average deviation from each of the ten individual deviations.

See Figure 2.1.3 column B.

4) Starting with the first deviation from average, sum up all the deviations from average through each of the ten taps. For example the cumulative sum for the third tap would be the sum of the first, second and third deviations from average, for the example shown in Figure 2.1.3 this would be 0.4+2.4-2.6= 0.2.

See Figure 2.1.3 column C. The last figure in this column should always be zero.

5) Divide each of the cumulative sums by ten to get the linearity deviation at each tap.

See Figure 2.3.1 column D.

The calibrated SR 1010 can now be used as a standard divider for calibrating other dividers. The following outlines the procedure for comparing the two.

6) Connect the SR 1010 and a microvoltmeter to the divider to be calibrated as shown in Section 2.2.4.

7) Adjust the end correcting potentiometers as described in Figure 2.2.4b.

8) Connect the microvoltmeter between corresponding taps on the SR 1010 and divider to be calibrated, and measure the deviation of the output of the unknown divider from the output of the SR 1010 at each tap.

The linearity deviation of the unknown divider will be

$$L^r_{unk} = \frac{V_{\mu v}}{E_{in}} + L^r_{std}$$

where:

L^r_{unk} is the linearity deviation of the unknown divider at the rth tap.

$V_{\mu v}$ is the reading of the microvoltmeter.

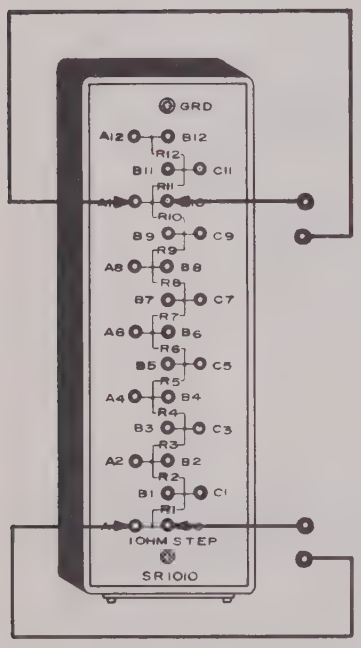
E_{in} is the voltage applied to the input of the dividers.

L^r_{std} is the linearity deviation of the SR 1010 for corresponding tap. (Column D)

2.2 CONNECTIONS

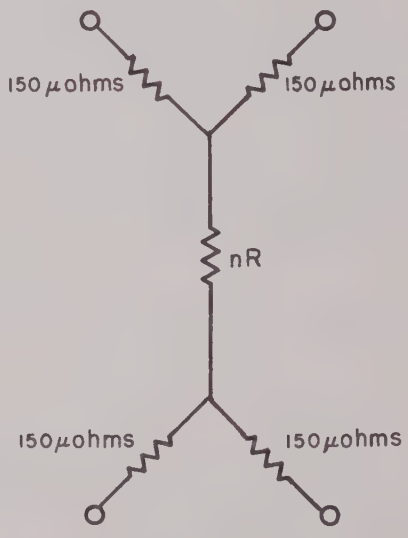
2.2.1 SINGLE RESISTOR OR SERIES GROUP

The SR 1010 was designed for use as a four-terminal resistor. The four connections are made to the two pairs of binding posts at either end of any of the resistors. The resistors are internally connected in series; to connect to n resistors in series it is only necessary to connect to the opposite ends of the 1st and nth resistors, see Figure 2.2.1a.



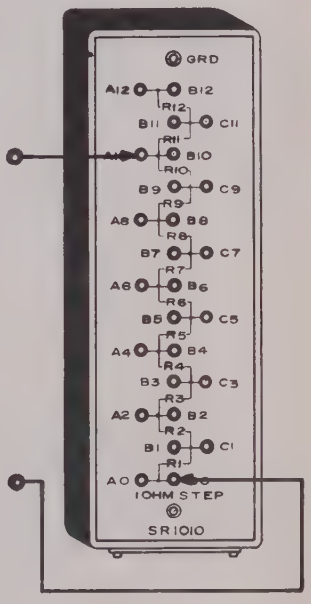
Four-terminal connection of ten resistors in series.

FIG. 2.2.1a



Equivalent circuit of n resistors in series.

FIG. 2.2.1b



Two-terminal connection of ten resistors in series.

FIG. 2.2.1c

The junction design that connects the resistors in series and to the binding post terminals is such that it contributes less than one microhm resistance to that of a four-terminal measurement of the individual resistors.

The SR 1010 may also be used as a two-terminal resistor; however, the calibrated four-terminal value must be corrected for the terminal resistance. Due to the design of the terminals at the end of each resistor it makes no difference which one is used for a two-terminal measurement. The resistance contributed by these terminals will be within ±0.06 milliohms of the resistance measured between the pair of terminals connected to the same end of any resistor, (about 0.3 milliohms), see Figure 2.2.1d.

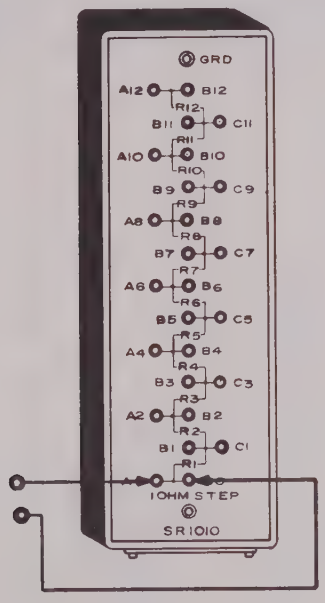
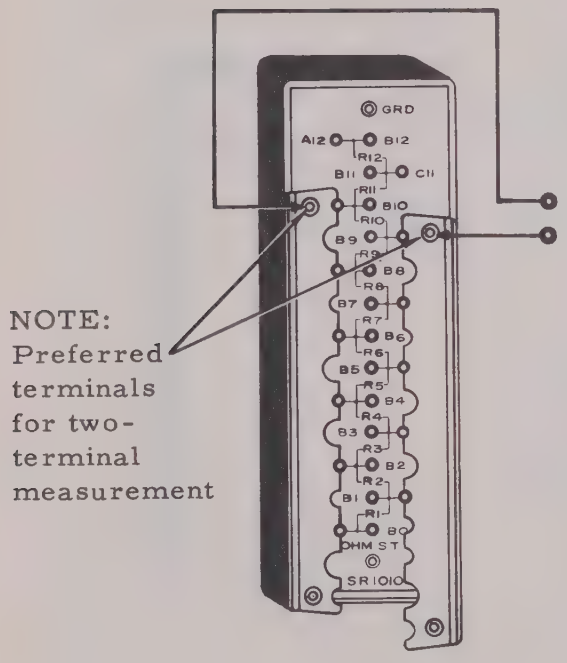


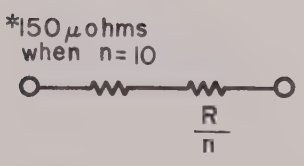
FIG. 2.2.1d

2.2.2 PARALLEL GROUP OF RESISTORS

Any number of resistors of a SR 1010 can be connected in parallel by means of shorting bars (ESI MODEL SB 103 or equivalent), see Figure 2.2.2a. For individual resistors of less than one hundred ohms, the paralleling leads and contact resistance may cause significant errors.

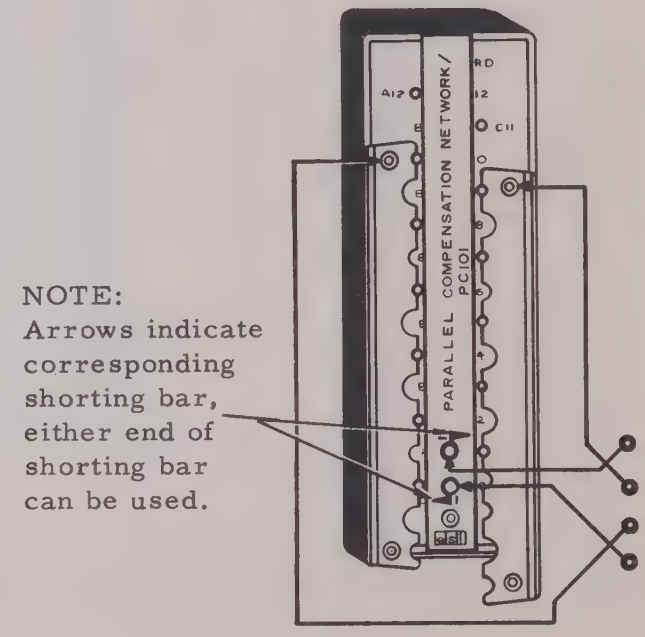
In connecting ten resistors in parallel, these errors can be essentially eliminated by use of a special compensation network for making four-terminal parallel connections (ESI MODEL PC 101 PARALLEL COMPENSATION NETWORK), see Figure 2.2.2b.

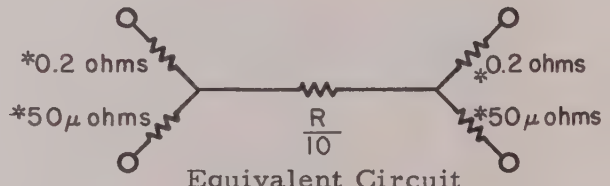




Equivalent Circuit

FIG. 2.2.2a


NOTE:
Arrows indicate corresponding shorting bar, either end of shorting bar can be used.
PARALLEL COMPENSATION NETWORK / PC 101



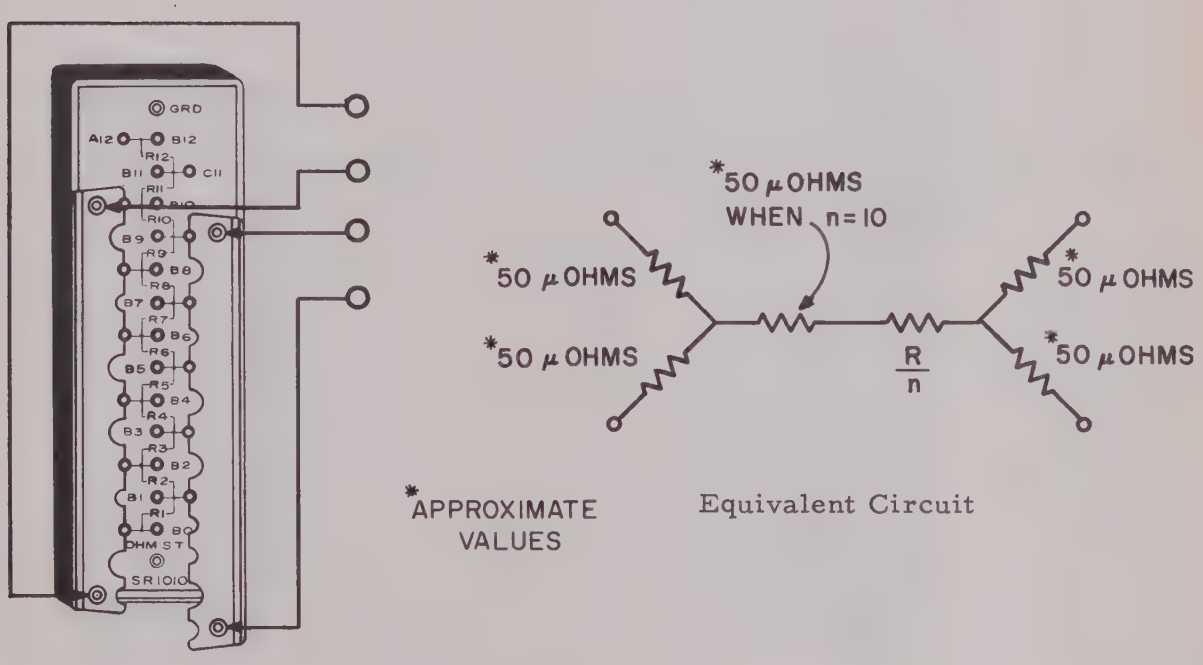
Equivalent Circuit

*APPROXIMATE VALUES

FIG. 2.2.2b

It should be noted that the resistance in series with the terminals to the compensation network is considerably higher than that in series with the terminals to the shorting bars, see Figure 2.2.2b. When connecting this paralleled group of resistors and compensating network to a bridge or ratio set care should be taken to connect these higher resistance terminals where they will least affect the accuracy of the measurement.

A simplified four-terminal parallel connection of any number of resistors can be made using only the shorting bars as shown in Figure 2.2.2c. This places a small connection resistance in series with the paralleled resistance. However, since there will be several contacts in parallel it will be a fairly stable and reproducible resistance and can be subtracted from the measured value, see Figure 2.2.2c.

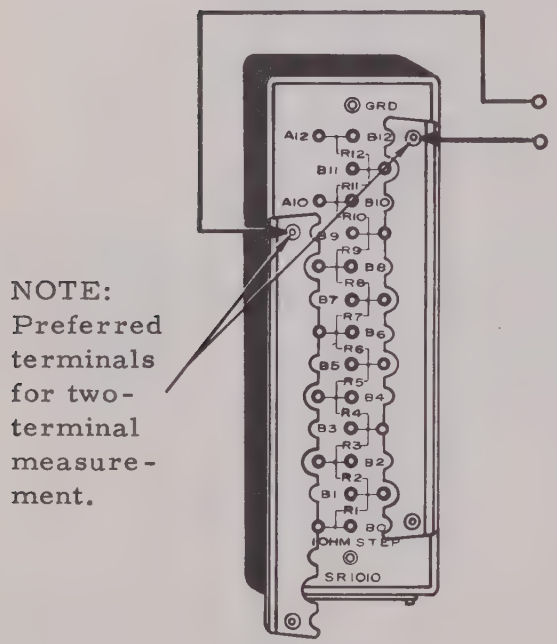


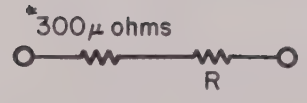
Simplified four-terminal parallel connection.

FIG. 2.2.2c

2.2.3 SERIES-PARALLEL GROUP OF RESISTORS

In addition to the series and parallel connections, series-parallel connections of the SR 1010 are also possible. With this method nine resistors, three parallel groups of three resistors in series, may be used to form a stable resistor equal in value to the individual resistors in the string. The ESI MODEL SB 103 SHORTING BARS can be used for this type of connection also, see Figure 2.2.3a. For individual resistors of less than one hundred ohms resistance, the paralleling leads and contact resistance may cause significant errors. These errors can be essentially eliminated by use of a special compensation network for making four-terminal series-parallel connections (ESI MODEL SPC 102 SERIES-PARALLEL COMPENSATION NETWORK). Such a network is shown connected to a SR 1010 in Figure 2.2.3b.

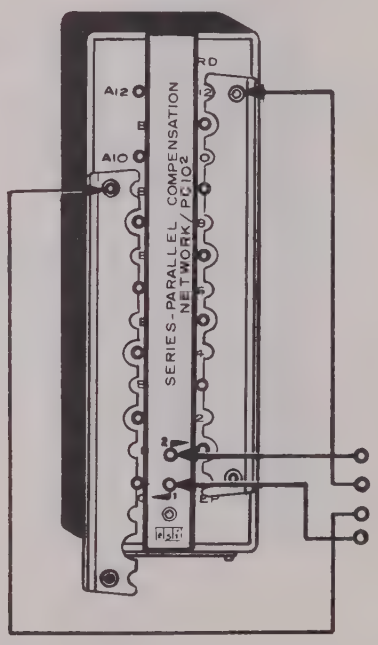


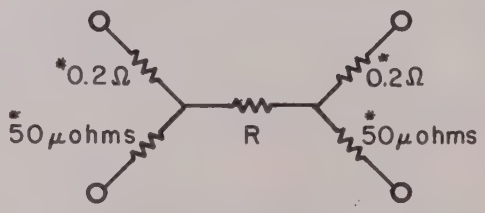


Equivalent Circuit

*APPROXIMATE VALUES

FIG. 2.2.3a



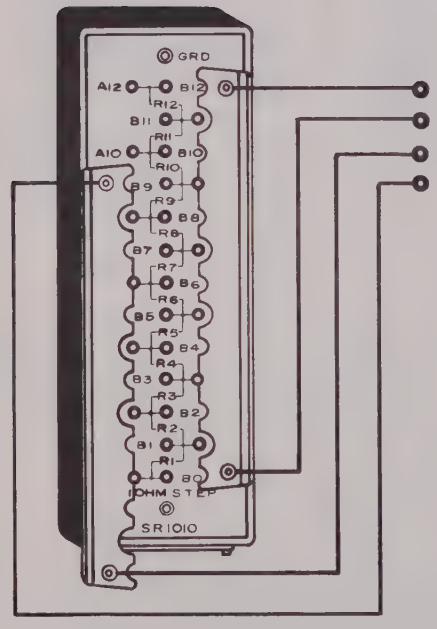


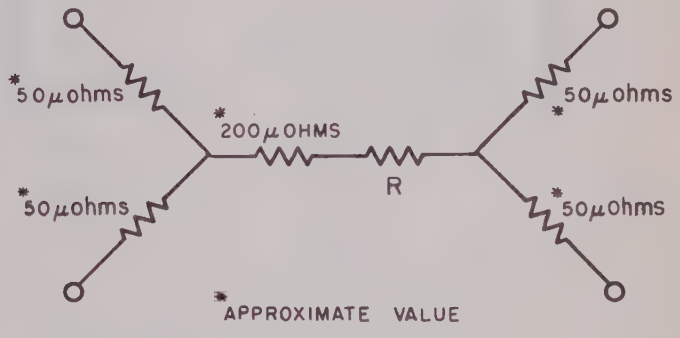
Equivalent Circuit

FIG. 2.2.3b

It should be noted that the resistance in series with the terminals to the compensation network is considerably higher than that in series with the terminals to the shorting bars, see Figure 2.2.3b. When connecting this paralleled group of resistors and compensating network to a bridge or ratio set care should be taken to connect these higher resistance terminals where they will least affect the accuracy of the measurement.

A simplified four-terminal series-parallel connection can be made using only the shorting bars as shown in Figure 2.2.3c. This places the connection resistance of the shorting bars in series with the series-paralleled resistance. However, since there will be several contacts in parallel it will be a fairly stable and reproducible resistance and could be subtracted from the measured value, see Figure 2.2.3c.





Equivalent circuit

Simplified four-terminal series-parallel connection.

FIG. 2.2.3c

2.2.4 DIVIDER CONNECTIONS

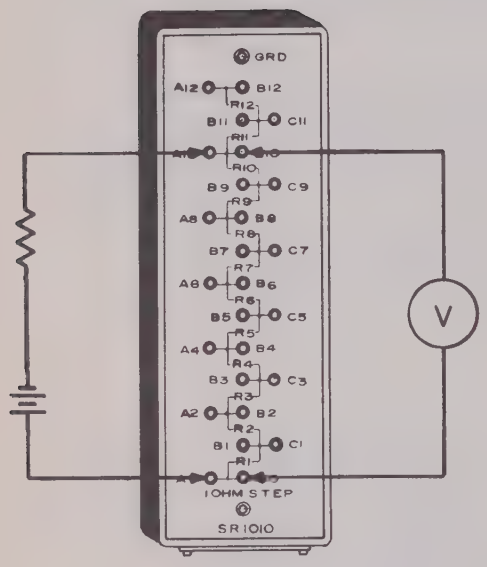


FIG. 2.2.4a

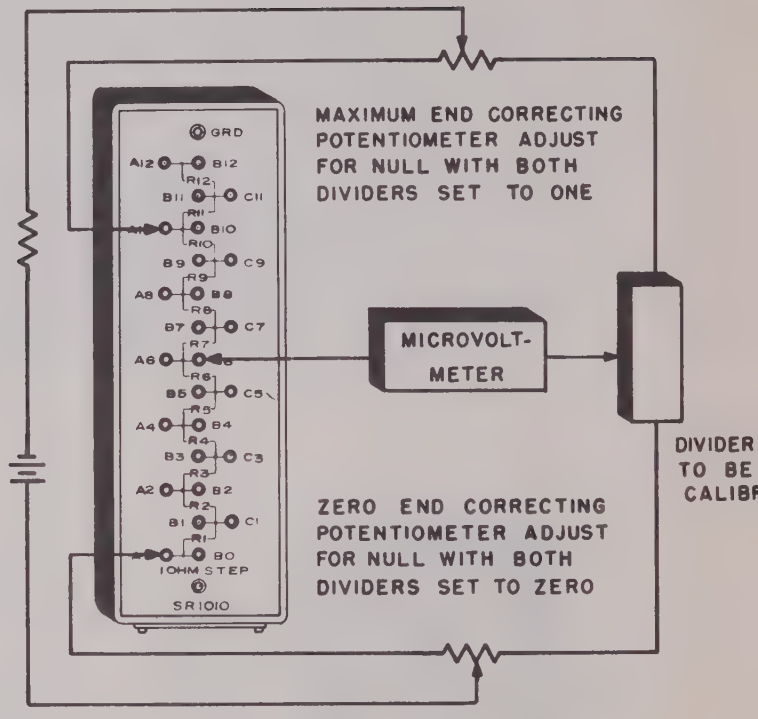


FIG. 2.2.4b

Connections to the SR 1010 for use as a voltage divider should be made as shown in Figure 2.2.4a. The source is connected to terminals A0 and A10 and adjusted to the desired open circuit voltage at terminals B0 and B10. The rest of the taps will then be correct in interpolating between B0 and B10.

For calibrating another divider with a SR 1010 an additional accessory is required for compensating for lead and contact resistances, an ESI MODEL LC 875 VOLTAGE DIVIDER LEAD COMPENSATOR or equivalent is recommended. The lead compensator is connected between terminals B0, B10 and the input of the divider to be calibrated, see Figure 2.2.4b. With the detector connected between A0 and the minimum end of the divider to be calibrated the lead compensator is adjusted for a detector null. Change the detector connections to A10 and the maximum end of the detector to be calibrated and adjust the lead compensator for a detector null. The divider to be calibrated may then be accurately compared to the SR 1010 at integral multiples of one tenth the full scale voltage.

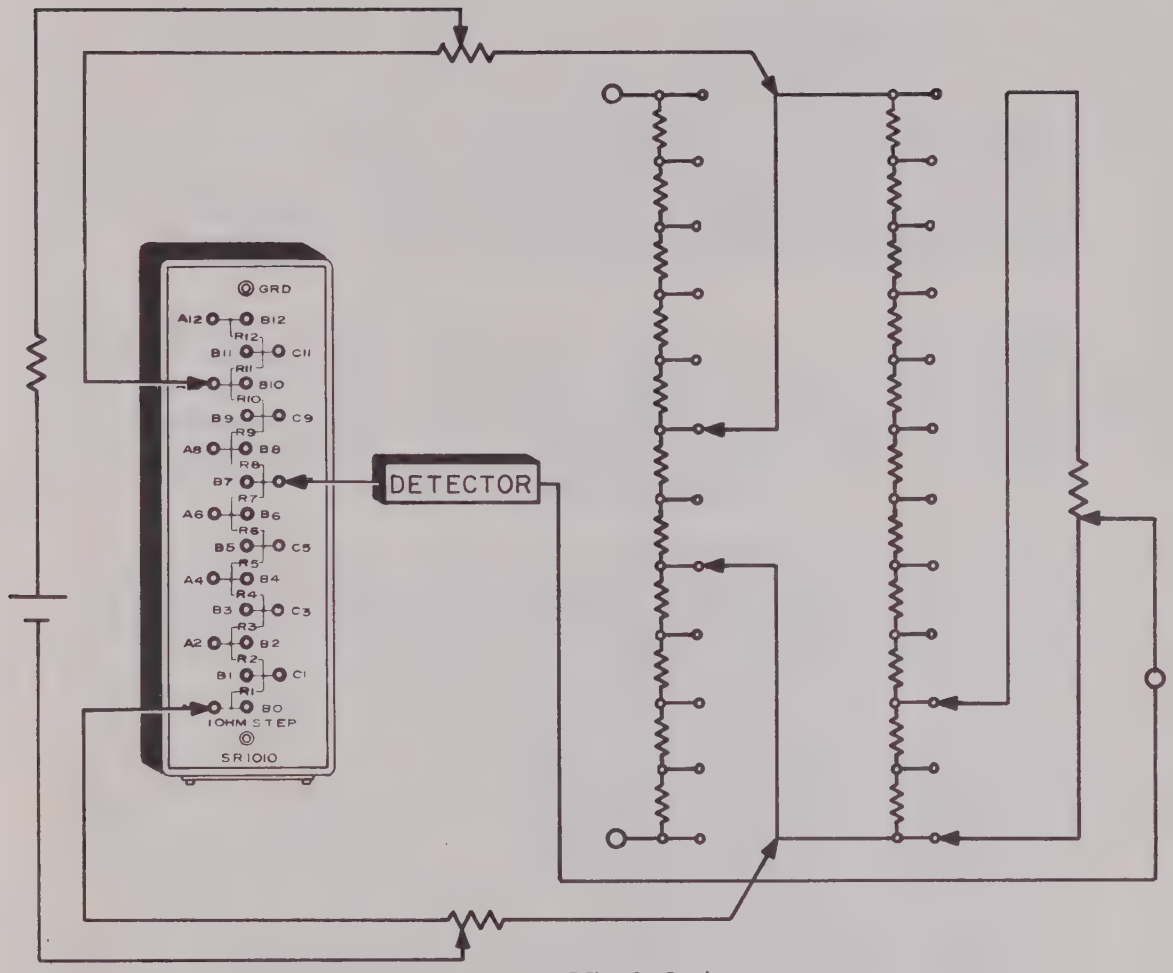


FIG. 2.2.4c

For calibrating other than the first decade of a Kelvin-Varley voltage divider it is necessary to connect the generator to the input of the decade under calibration. This will normally require making an internal connection to the divider, see Figure 2.2.4c. This method gives a complete, high accuracy calibration of the whole Kelvin-Varley divider, including all lead and switch resistances.

2.3 HIGH ACCURACY CALIBRATION TRANSFER

2.3.1 INTRODUCTION

To make resistance measurements of the highest possible accuracy, the measurement should be traced at the time it is measured to the highest accuracy resistance standard available. This standard will be called the reference standard.

At the present state of the art, the highest accuracy for a reference standard can be obtained only at the one ohm level, using one or more Thomas pattern one ohm standard resistors. These resistors are certified by the National Bureau of Standards to an accuracy of ±2 parts per million, after they have been observed for a sufficient length of time to verify their stability.

This section describes the procedures for making measurements over a wide resistance range with accuracies approaching that of the reference standard available, using a set of SR 1010 RESISTANCE TRANSFER STANDARDS and a Kelvin comparison bridge or double ratio set capable of comparing equal resistors to one ppm.

The name RESISTANCE TRANSFER STANDARD refers to the ability of the MODEL SR 1010 to be measured at one resistance level and used with equal accuracy at a different resistance level. In a series of measurements using such transfers to trace calibration from a reference standard to an unknown resistor, neither the absolute value nor the long term stability of the resistors in the SR 1010s or the bridge used for comparisons has any effect on the measurement accuracy. The burden of calibration accuracy and long-term stability is placed on the reference standard alone; the concern with the rest of the system need be only with its short-term stability during the period of a few minutes required to complete the measurement. With careful operating technique in a normal laboratory environment, each step in such a series of measurements can be accurate to one or two ppm.

In making such a chain of measurements, one of the advantages of using a set of ten resistors connected as in the SR 1010 is that a 100 to 1 transfer in resistance level can be made at each measurement, minimizing the accumulation of errors. For example, the limits of error in measuring a one megohm resistor might be assumed as follows:

Certified accuracy of 1 ohm standard	2 ppm
Comparison of 1 ohm standard with 10 ohm SR 1010 (connected for 1 ohm)	2 ppm
Comparison of 10 ohm SR 1010 with 1 kilohm SR 1010 (both connected for 100 ohms)	2 ppm
Comparison of 1 kilohm SR 1010 with 100 kilohm SR 1010 (both connected for 10 kilohms)	2 ppm
Comparison of 100 kilohm SR 1010 (connected for 1 megohm) with unknown 1 megohm resistor	2 ppm
Total	10 ppm

The use of such a procedure for measuring any resistance value other than one ohm can be seen to be substantially more accurate than could be obtained by certification of standards presently available at values other than one ohm.

For highest accuracy, such a procedure may be repeated each time a new measurement is made. If, during such measurements, a record is kept of the calibration of each SR 1010 used, a quantity of data will soon be accumulated with a minimum of effort. This data will indicate the stability of the SR 1010 and/or the variations in calibration resulting from changes in ambient conditions, operators or techniques. It can serve to indicate the actual accuracy of the data on the calibration chart under the laboratory conditions prevailing, and it will indicate when it is time to replace the calibration chart and supply dependable data for a new chart.

2.3.2 MAKING EQUAL RESISTANCE COMPARISONS

The comparison of like resistance values can be made independent of the absolute accuracy and long-term stability of the comparison bridge by using either an interchange or a substitution method. A direct-reading double ratio set, such as the ESI MODEL 240 KELVIN RATIO BRIDGE, for making four-terminal comparison measurements with a 1 ppm resolution and short-term stability, should be used for calibration transfer with SR 1010s.

The following outlines the procedure for comparing two resistors by the interchange method:

1) With the standard resistor or previously calibrated SR 1010 connected to the standard terminals of the bridge and the unknown

resistor or SR 1010 to be calibrated connected to the unknown terminals, balance the bridge and determine the deviation of the unknown from the standard. Call this reading d_1.

2) With the unknown resistor connected to the standard terminals and the standard resistor connected to the unknown terminals, balance the bridge and determine the deviation of the standard from the unknown. Call this reading d_2.

3) Calculate $\frac{d_1 - d_2}{2}$ this is the deviation of the unknown resistor from the standard resistor. To obtain the deviation of the unknown resistor from nominal value, add to this calculated value the deviation of the standard resistor from nominal value.

To compare two resistors by the substitution method, connect to the standard terminals of the bridge a working standard resistor of the required value and make two measurements, the first with the standard resistor or previously calibrated SR 1010 connected to the unknown terminals, and the second with the unknown resistor or SR 1010 to be calibrated connected to the unknown terminals. The difference between these two readings will be the difference between the two resistors.

The substitution method is particularly convenient when either the working standard or the bridge ratio can be adjusted to make the bridge deviation dial read deviation from nominal value directly. The procedure is then modified so that when the known resistor is connected to the unknown terminals, the deviation dial is adjusted to its known deviation from nominal value and the working standard or ratio calibration adjustment is used to balance the bridge. When the known resistor is disconnected and the unknown connected to the unknown terminals, the deviation dial at balance will indicate directly the deviation of the unknown resistor from nominal value.

In a series of calibration transfer measurements in which the unknown resistance in one comparison and the known resistance in the next consist of the same group of resistors differently connected, the deviation reading in the first comparison becomes the initial deviation setting for the next measurement. Thus the dial setting serves as a mechanical memory and indicates the actual deviation value through the whole series of measurements, including the final reading on the unknown resistor.

The ESI MODEL RS 925 DECADE RESISTANCE STANDARD makes an excellent adjustable, four-terminal working standard with a 1 ppm resolution at settings of 100 ohms and above. The 100 ohm setting of the RS 925 can be used for measurements by the substitution method

at 1 and 10 ohms if the bridge has ratios of 10 to 1 and 100 to 1. The ESI MODEL 240 KELVIN RATIO BRIDGE provides these ratios, though at somewhat reduced accuracy as a result of sensitivity to lead resistance errors in the connection to the unknown. To retain the full accuracy of the 1 to 1 ratio of the Model 240 bridge for measurements at 1 and 10 ohms, another SR 1010 can be used as a fixed working standard -- use the 1 ohm box as a working standard when calibrating the 10 ohm box, and vice versa.

2.3.3 USING A CERTIFIED RESISTANCE STANDARD

It is necessary to begin any chain of transfer measurements with a very accurately known and highly stable standard resistor. The Thomas pattern one ohm resistor is such a resistor and is recommended for this purpose. These resistors are commercially available and many of them are certified to an accuracy of ±2 ppm per year. In high-accuracy calibration transfer measurements, the Thomas pattern one ohm resistor is used to calibrate the nine-resistor series-parallel configuration of the 1 ohm SR 1010 or the ten-resistor parallel configuration of the 10 ohm SR 1010.

The following suggestions will aid in making measurements at the one ohm level with maximum accuracy:

1) Operate the Thomas pattern resistor in oil in order to minimize its temperature rise with power dissipation and to allow accurate measurement of the resistor temperature. If accurate temperature coefficient data is available for the resistor (α and β terms), a small unstirred pot of oil at room temperature is quite adequate. Measure the oil temperature to an accuracy of ±0.2°C and calculate the value of the resistor at this temperature.

2) To avoid internal heating of the standard and the SR 1010, use reduced input power to the bridge for the initial balance adjustment, then increase power to approximately one half watt (2/3 amp through standard and unknown) for only a few seconds, to make the final accurate balance adjustment. Both the Thomas pattern resistor and the SR 1010 will typically remain constant within 1 ppm for approximately 10 seconds at this power level.

3) When using 1 ohm and 10 ohm SR 1010 boxes, complete their comparison with the reference standard and their use in calibrating higher value SR 1010s in as short a time as possible, in order to

keep all the measurements at as nearly the same temperature as possible. The exact temperature of an SR 1010 in calibration transfer is unimportant, but its temperature must remain sufficiently constant throughout the procedure. This is particularly important with the 1 and 10 ohm boxes, since they have higher temperature coefficients then the higher value boxes.

In changing the connections to the SR 1010, avoid unnecessary handling, in order to minimize temperature changes.

2.3.4 CALIBRATION TRANSFER BETWEEN SR 1010 BOXES

In calibration transfer measurements, the three most commonly used connection configurations for the SR 1010s are ten resistors in parallel, nine resistors in series-parallel, and ten resistors in series, yielding resistance values of 0.1, 1 and 10 times the individual resistor value. It is always preferable to use one of these groups of resistors in preference to any single resistor, in order to minimize temperature rise with internal heating and to take advantage of averaging of temperature coefficients of the various resistors in the box.

The basic absolute resistance calibration of an SR 1010 box is accomplished by accurately measuring any one of these three connection configurations. Once the reference standard or a previously calibrated SR 1010 has been used to calibrate one of these three configurations for a box, the values for all other resistor configurations are obtained by calculation using this value with selected measurements of the resistors in the same box relative to one another or relative to the nine-resistor series-parallel configuration having the same resistance value.

For 1 ppm accuracy in calibrating or using the ten resistor parallel and nine resistor series-parallel configurations, the PC 101 and SPC 102 compensation networks must be used with the 1 ohm and 10 ohm boxes, and with the 100 ohm box unless a correction is made for terminal resistance. The simplified four-terminal connection using the SB 103 shorting bar pair alone is adequate for SR 1010s having values of 1 kilohm per step or higher (see Section 2.2).

The recommended sequence for calibration transfer to the various SR 1010 boxes is as follows:

SR 1010 (ohms/step)	Connection	Number of Resistors	Compared to
1	Series-Parallel	9	One Ohm Reference Standard
10	Parallel	10	
100	Series-Parallel	9	10 ohm per step SR 1010 ten resistors in series
1K	Parallel	10	
10K	Series-parallel	9	1 kilohm per step SR 1010 ten resistors in series
100K	Parallel	10	

2.3.5 CALIBRATION TRANSFER BETWEEN PRINCIPAL CONFIGURATIONS

The majority of calibration transfer applications require the use of only the three principal resistance configurations for the SR 1010 boxes; for these measurements, the individual resistors need never be calibrated. This is the key to both the high accuracy and the extreme simplicity of this transfer technique.

The basic rule relating resistor configurations is that all configurations which use the same group of resistors and distribute the power equally among them have the same deviation from the nominal values for the configurations; this deviation is equal to the average of the deviations of the individual resistors in the group from their nominal value. (This is true to one part in 10^9 for the resistor matching used in SR 1010s).

Thus ten resistors in series will have exactly 100 times the resistance of the same ten resistors in parallel, or nine resistors in series-parallel will have exactly nine times their resistance in parallel, or exactly one ninth of their resistance in series. Thus when a resistor group is calibrated in one configuration and exactly the same group used in another configuration at a different resistance level, no further measurements are necessary and no calculations are required.

To transfer calibration between the ten resistor group and the nine resistor group, the difference between the tenth resistor and the nine-resistor series-parallel configuration must be measured* in order to calculate the average deviations of the two groups.

The formula relating the average deviation of one group to that of the other, to calculate one when the other has been measured, is:

$$d^{9}_{av} - d^{10}_{av} = 0.1\ (d^{9}_{av} - d_{10})$$

in which:

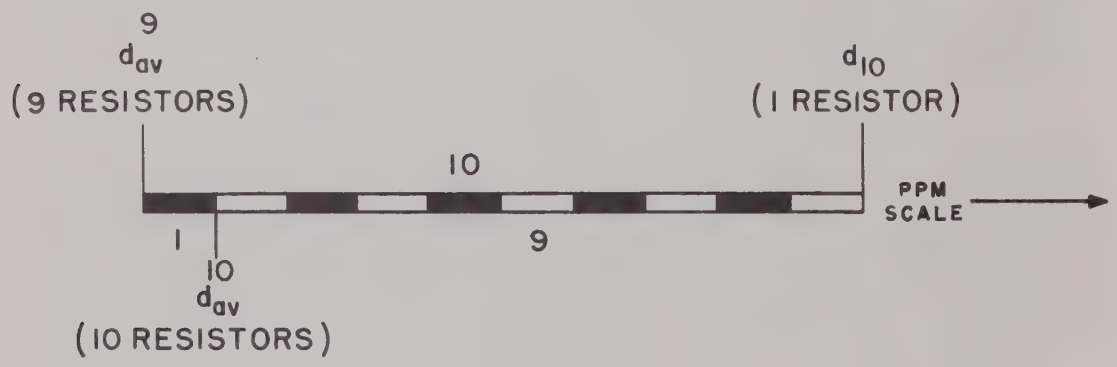
d^{9}_{av} is the average deviation of the nine resistor group from nominal.

d^{10}_{av} is the average deviation of the ten resistor group from nominal.

d_{10} is the deviation of the tenth resistor from nominal.

$(d^{9}_{av} - d_{10})$ is the measured difference between the nine-resistor series-parallel configuration and the tenth resistor.

This formula can be visualized as a weighted average on a diagram as follows:



*For box values requiring the use of the compensation networks, this measurement must be made by the substitution method, rather than the interchange method, since the network must be removed to connect to the tenth resistor for measurement.

Note that the measured difference is multiplied by one tenth; thus if the measurement by the substitution method is accurate to 1 or 2 ppm, the calculated difference between the groups will be correct to 0.1 or 0.2 ppm, which can be considered negligible compared with the accuracy to which the measured group is known.

2.3.6 CALIBRATION TRANSFER TO INDIVIDUAL RESISTORS

To calibrate the individual resistors of a SR 1010 it is recommended that the deviation from nominal of a series or parallel group of ten, or a series-parallel group of nine be determined as accurately as possible by comparison to a known reference standard. Next each of the individual resistors must be compared to a stable working standard to determine their deviations relative to one another. From these relative deviations the average deviation for the group first measured is calculated. The difference of this measured deviation from nominal minus the calculated average deviation is added to each of the individual deviations to determine the deviation from nominal of the individual resistors.

A step by step procedure for calibrating the individual resistors of a complete set of SR 1010s is given in Section 4.3.1 and 4.3.2 and is exemplified in Section 4.3.3.

2.3.7 CALIBRATION OF AN SR 1010 AS A TEN-STEP DIVIDER

Since ratio measurements do not depend upon any absolute resistance standard, no reference standard of resistance is required to calibrate an SR 1010 as a divider. The procedure for calibrating an SR 1010 as a divider with ten equal steps is as follows:

1) Connect a stable working standard, whose nominal value is equal to that of the individual resistors of the SR 1010 to be calibrated, to the standard terminals of the bridge. This standard may be ten resistors in series (or parallel) of the SR 1010 whose resistance per step is one tenth (or ten times) that of the SR 1010 to be calibrated.

2)	Measure d_n, the deviation of each of the first ten resistors in the string from that of the standard resistor.	The calibration of the bridge or the accuracy of the working standard need not be considered, only their short term stability is of importance.
3)	Calculate the average deviation, d_{av}^{10}, of the ten measured deviations, d_n.	$d_{av}^{10} = 0.1 \sum_{n=1}^{10} d_n$
4)	Subtract the average deviation, d_{av}, from each deviation d_n.	$(d_n - d_{av}^{10})$
5)	Sum these differences to each tap and divide by ten to get the linearity deviation at the tap.	$L_r = 0.1 \sum_{n=1}^{n=r} (d_n - d_{av}^{10})$

where:

L_r (ratio error) is the linearity deviation at the rth tap. Linearity deviation is defined as the difference between actual tap value and nominal tap value expressed as a proportional part of full scale.

A sample tabular calculation of steps 3), 4), and 5) will be found in Figure 2.1.3.

SECTION III

THEORY

3.1 JUNCTION RESISTANCE EFFECTS

FIG. 3.1a

The series configuration of the SR 1010 TRANSFER STANDARD is shown in Figure 3.1a. The four-terminal resistors can be measured individually or in any series combination. If the measured series resistance is to be equal to the sum of the individual resistor measurements, the junctions must have zero four-terminal resistance. This junction transresistance is zero if a current source connected to any two of the four junction terminals produces zero voltage difference between the other two terminals.

In practice, the junctions do have some transresistance. It is possible to make the resistance very low (much less than 1 microhm) by proper design. For instance, if four terminals are connected to a plane sheet of metal in the configuration shown in Figure 3.1b, two of the terminals will always be on an equipotential line if a current source is connected to the other two terminals.

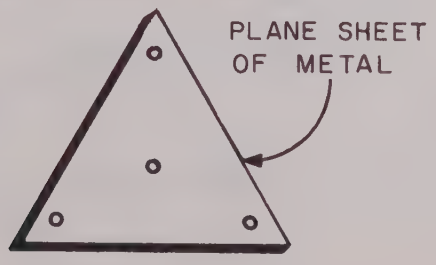


FIG. 3.1b

The tests for a four-terminal point junction are shown in Figure 3.1c. The meter voltages divided by the generator currents are the transresistances for the two connections shown. A third transresistance, shown in Figure 3.1d need not be measured, since it is always equal to the difference between the other two (note that each reading in Figure 3.1c may be either positive or negative; keep this sign when subtracting to calculate third transresistance).

These three transresistances represent the greatest possible resistance measurement error. For the junction in the SR 1010 each of these three resistances is less than 0.5 microhm, causing much less than one ppm error for even a one ohm per step box.

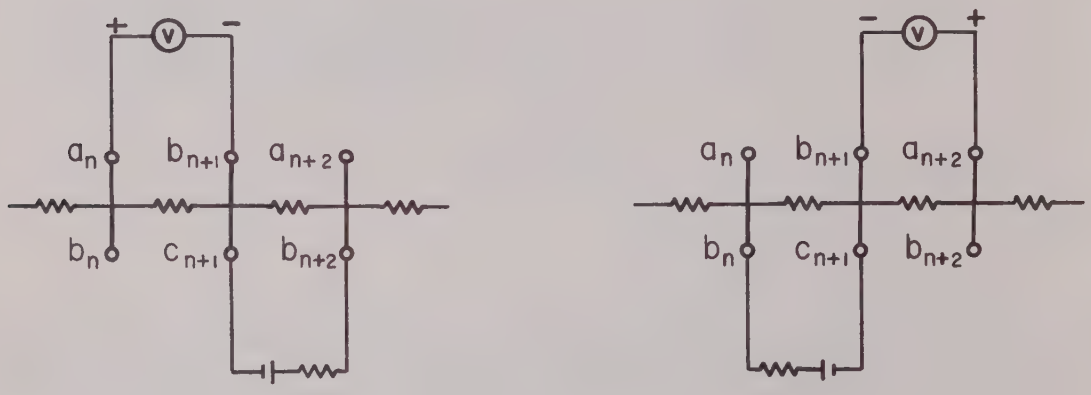


FIG. 3.1c

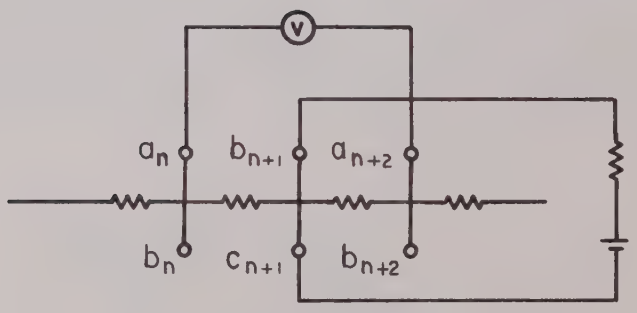


FIG. 3.1d

3.2 INSULATION RESISTANCE EFFECTS

The leakage resistance of the SR 1010 to its case is in excess of 10^{12} ohms. For worst case conditions (twelve one hundred kilohm resistors in series with one end of the SR 1010 tied to its case) the error due to shunt resistance will be less than 1.2 ppm.

If a three terminal measurement is made (the case being the third terminal) and again worst case conditions assumed (twelve resistors in series with all leakage being concentrated from the center point of the series string) the following wye-delta transformation is necessary to determine the resulting error.

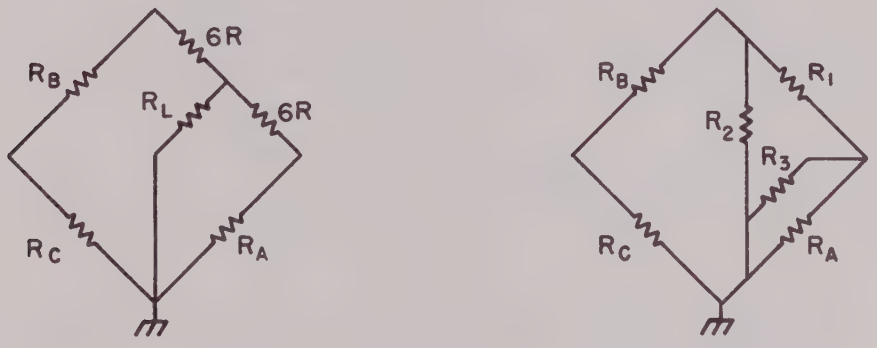


FIG. 3.2

where:

R_A, R_B and R_C are the ratio arms of the bridge.
R is the resistance per step of the SR 1010.
R_L is the leakage resistance from the SR 1010 to its case.

$$R_1 = \frac{36R^2}{R_L} + 12R = 12R(1 + \frac{3R}{R_L})$$

R_2 is across the generator or detector so can be neglected.

$$R_3 = 2R_L + 6R$$

For a one hundred kilohm per step box $R_1 = 12R(1 + 0.3 \text{ ppm})$ and $R_3 = 2 \times 10^{12}$.

If R_A is no greater than one hundred kilohms the error will not exceed 0.3 ppm.

Since leakage resistance will lower the measured resistance in a two-terminal measurement and increase it in a three-terminal measurement the actual resistance must lie between these two values. This fact can be used as a check to determine the magnitude of the error due to leakage resistance.

3.3 BASIC TRANSFER ACCURACY

To make transfer measurements which do not depend on the absolute accuracy of the transfer standard but only on its short term stability, it is necessary to assume that ten resistors in parallel are exactly equal to one one hundredth of the same ten resistors in series. To see how valid this assumption is let R be the nominal value of the individual resistors and d_n the deviation from nominal of this nth resistor. The value of the nth resistor will then be $R_n = R(1 + d_n)$. The value of the ten resistors in series will be:

$$R_s = \sum_{n=1}^{10} R(1 + d_n) = 10R\left(1 + \frac{1}{10}\sum_{n=1}^{10} d_n\right)$$

$$d_{av}^{10} = \frac{1}{10}\sum_{n=1}^{10} d_n$$

where: d_{av}^{10} is the average of the deviation d_n for ten resistors.

$$R_s = 10R(1 + d_{av}^{10})$$

The resistance of the same ten resistors in parallel will be:

$$R_p = \frac{1}{\sum_{n=1}^{10} \frac{1}{R(1 + d_n)}}$$

$$\frac{1}{R(1 + d_n)} = \frac{1}{R}(1 - d_n + {d_n}^2 - {d_n}^3 \ldots\ldots)$$

$$R_p = \frac{1}{\sum_{n=1}^{10} \frac{1}{R}(1 - d_n + {d_n}^2 \ldots\ldots)}$$

$$R_p = \frac{R}{10} \frac{1}{1 + \frac{1}{10}\sum_{n=1}^{10}(-d_n + {d_n}^2 \ldots\ldots)}$$

$$R_p = \frac{R}{10}\left(1 + \frac{1}{10}\sum_{n=1}^{10} d_n - \frac{1}{10}\sum_{n=1}^{10} d_n^2 \cdots\cdots\right)$$

$$R_p = \frac{R}{10}\left(1 + d_{av}^{10} - \frac{1}{10}\sum_{n=1}^{10} d_n^2 \cdots\cdots\right)$$

$$R_p \approx \frac{R}{10}\left(1 + d_{av}^{10}\right)$$

The assumption being that $\frac{1}{10}\sum_{n=1}^{10} d_n^2$ is negligible. Since d_n maximum for the SR 1010 is less than 100 ppm d_n^2 will be less than 0.01 ppm which can be neglected, thus the original assumption is quite valid. A similar analysis can be made for the series-parallel connection or any other configuration in which the power divides equally among the resistors.

3.4 FOUR-TERMINAL PARALLELING

The parallel connection of ten four-terminal resistors is shown in Figure 3.4a.

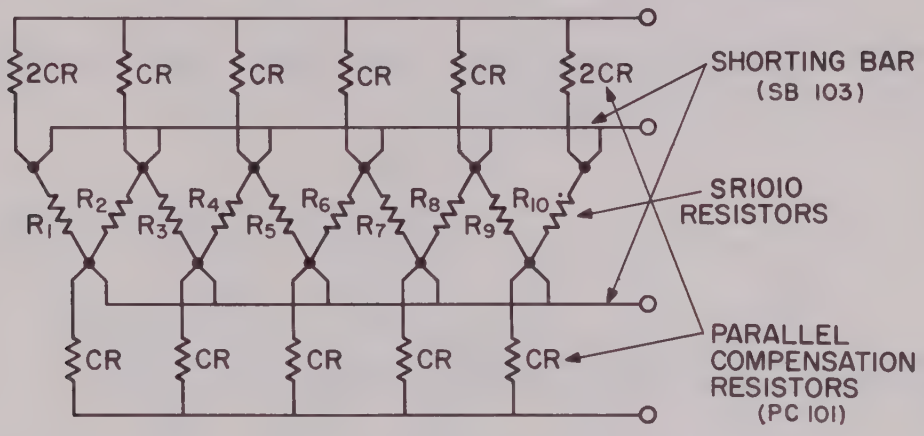


FIG. 3.4a

FIG. 3.4a TEN FOUR-TERMINAL RESISTORS IN PARALLEL

The shorting bar resistance and the resistance from the junctions to the shorting bars should be small. The parallel-compensation resistors should be large compared to the uncertainty in the contact resistances when they are connected and should be proportional to the resistance of the SR 1010 resistors. The two parallel-compensation resistors on the ends are double the others because they connect to one build-up resistor instead of two in parallel.

When several nominally equal resistors are connected in parallel the connection accuracy can be analyzed by assuming all of the compensation resistors except one are equal, and that all of the bus bar resistances except one are zero. At the same time all of the resistors being connected are assumed to be perfect except one. The three imperfect resistors all meet at one of the junctions. Since small first order error effects add linearly the results of this analysis can be extended to determine the connection accuracy. The connection uncertainty is less than:

$$\pm 2\left(\frac{r}{R}\right)\left(d_{CR} - d_R\right)$$

where:

r is the greatest bus bar resistance
R is the nominal value of resistors being parallel connected
$(d_{CR} - d_R)$ is the greatest bridge unbalance in terms of resistance deviations of the compensation resistors and the resistors being connected

The values of $\frac{r}{R}$ and $(d_{CR} - d_R)$ can be measured to find the expected accuracy of a particular connection.

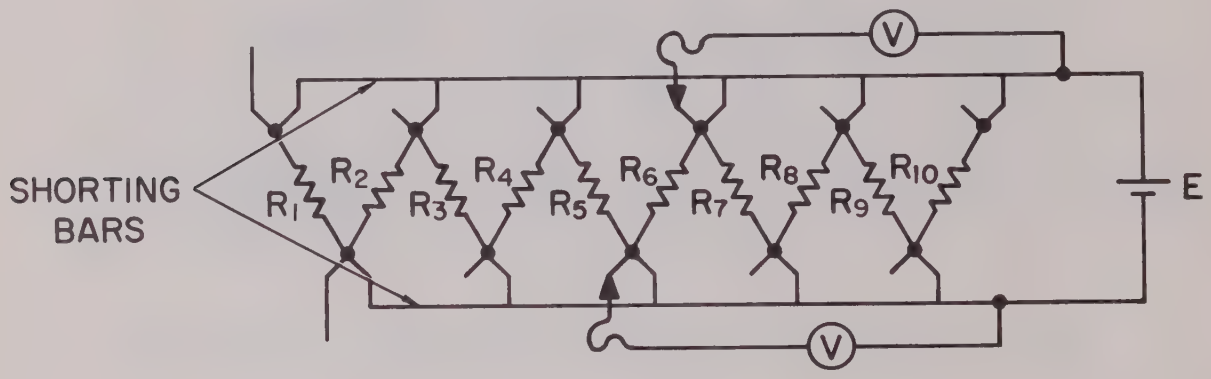


FIG. 3.4b

Connect the shorting bars.

Measure voltage from a point on the bars to the unused terminals, this is the voltage to the junction of adjacent resistors.

Find the maximum difference of values V for each bar.

Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\text{for } r \ll R \qquad \frac{V_{max} - V_{min}}{E} \approx (\frac{r}{R})_{max}$$

The value of $\frac{r}{R}$ can be found by measuring the voltage drops from a point on the bus bars to the junction of adjacent resistors, shown in Figure 3.4b.

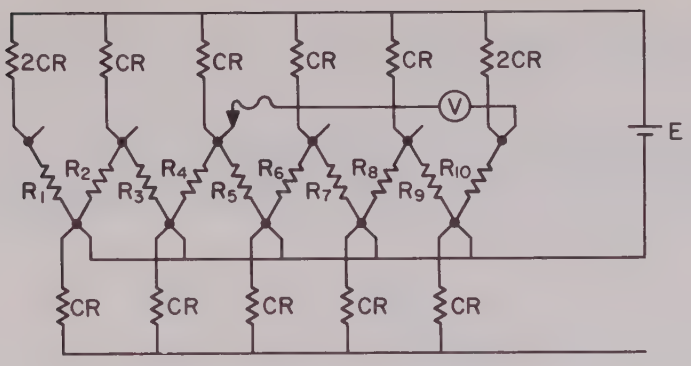


FIG. 3.4c

Connect the compensating network.

Connect the shorting bar.

Supply a voltage E from the shorting bar to the other side of the network.

Measure the voltage V from one unused shorting bar terminal to each of the others.

Change the shorting bar to the other side and repeat.

Find the maximum voltage difference $(V_{max} - V_{min})$ between terminals.

Calculate $(d_{CR} - d_R)_{max}$

$$\left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2CR}{R} + \frac{R}{R}\right) = (d_{CR} - d_R)_{max}$$

The bridge unbalance can be measured as shown in Figure 3.4c. The measured values of $\left(\frac{r}{R}\right)_{max}$ and $(d_{CR} - d_R)_{max}$ can be multiplied together and doubled to give an upper bound of the connection error. This usually includes a very substantial safety factor. The same technique can be used in the series-parallel case.

3.5 LINEARITY DEVIATION

To calibrate the SR 1010 as a voltage divider we need to know the difference between the actual ratio of the output to input voltages and the setting. This difference is called linearity deviation.

$$L = \frac{E_{out}}{E_{in}} - S$$

L - linearity deviation

E_{in} - actual input voltage

E_{out} - actual output voltage

S - divider setting

Since the voltage and resistance divide proportionately, the linearity deviation can be found by a precision comparison of the resistors in the divider string. By using ten resistors of the SR 1010 in the divider string, the output can be set to integral multiples of a tenth the input voltage. The linearity deviation for this divider can be written as:

$$L = \frac{\sum_{n=1}^{10S} R_n}{\sum_{n=1}^{10} R_n} - S$$

L - linearity deviation

R_n - resistance of nth resistor

$\sum_{n=1}^{10S} R_n$ - resistance from COM to OUT in ohms

$\sum_{n=1}^{10} R_n$ - total input resistance in ohms

S - divider setting

If all of the resistors in the string were equal, the voltage would divide equally. To find how far from the ideal this divider is each resistor, R_n, of the string is compared to a standard resistor. To maintain the ultimate in measurement accuracy four-terminal measurements should be made. The measured resistance deviation is used to calculate the linearity deviation.

$$R_n = R_s (1 + d_n)$$

R_n = resistance of nth resistor in ohms

R_s = resistance of standard resistor in ohms

d_n = per unit deviation of R_n from R_s

This leads to the following expression for linearity deviation:

$$L = \frac{\sum_{n=1}^{10S} (1 + d_n)}{\sum_{n=1}^{10} (1 + d_n)} - S$$

The precise value of the standard resistor is unimportant since it is canceled out of the equation, thus anyone of the resistors of the string can be used as the standard resistor. To simplify calculations the equation for linearity deviation can be modified by first defining the average deviation as $d_{av}^{10} = 0.1 \sum_{n=1}^{10} d_n$ and then assuming d_{av}^{10} is much smaller than one. The equation for linearity deviation can then be expressed as follows:

$$L = 0.1 \sum_{n=1}^{10S} (d_n - d_{av}^{10})$$

SECTION IV
CALIBRATION

4.1 INTRODUCTION

This section provides MODEL SR 1010 TRANSFER STANDARD calibration procedures for those that have the necessary facilities. Calibration should be performed in a laboratory environment. If this is not possible return the instrument to the factory or an authorized service facility for calibration.

Calibration of the SR 1010 for immediate use at highest accuracy is a part of the normal operating procedure, the detailed procedures are given in Section II. This section will contain comments related to systematic or routine calibration, and to special tests. These procedures will verify the performance of the whole SR 1010 calibration system, including the SB 103 SHORTING BARS, the PC 101 PARALLEL COMPENSATION NETWORK and SPC 102 SERIES-PARALLEL COMPENSATION NETWORK.

4.2 EQUIPMENT REQUIRED

1) Resistance reference standard: Preferably a Thomas pattern one ohm certified to at least 5 ppm.

2) Oil bath: Temperature regulated at certificate temperature of resistance standard or if temperature coefficient of the standard is known a thermometer with 0.1 °C steps for accurately determining the temperature of the oil bath can be used.

3) Comparison bridge: One to one Kelvin comparison bridge or direct reading ratio set for making four-terminal resistance comparisons. The resolution of the bridge and sensitivity of the associated detector should be sufficient to resolve 1 ppm deviations of the unknown from the standard for resistances from 1 ohm to 1 megohm. The short term stability should be better than 1 ppm. (ESI MODEL 240 KELVIN RATIO BRIDGE or equivalent).

4) Environmental requirements:

   Temperature: 23 °C ±1 °C
   Relative humidity: less than 60%, approximately 50%

5) Accessories:

   Shorting bars: paralleling straps for connecting ten resistors in parallel or nine in series-parallel. (ESI MODEL SB 103 or equivalent).
   Compensation networks: networks for making four-terminal parallel and series-parallel connections. (ESI MODELS PC 101 and SPC 102 or equivalent).

6) Microvoltmeter: With an input resistance of at least ten kilohms and on which less than one microvolt can be observed. (ESI MODEL 800 DC GENERATOR-DETECTOR recommended). A galvanometer can be used instead but it may be necessary to calibrate its sensitivity.

7) Current source: Approximately one amp current source; generator of ESI MODEL 800 can be used.

8) Voltage source: Approximately one hundred volt source; generator of ESI MODEL 800 can be used.

4.3 SEQUENCE OF CALIBRATION

4.3.1 CALIBRATION OF AVERAGE OF RESISTOR GROUPS

1) Connect the Thomas pattern one ohm standard resistor to the standard terminals of the comparison bridge. — See Figure 4.3.1a.

2) Connect nine resistors of the one ohm per step box in series-parallel using the series-parallel compensation network. — See Section 2.2.3 for proper series-parallel connections.

3) Connect these nine series-parallel resistors to the unknown terminals of the bridge. — See Figure 4.3.1a.

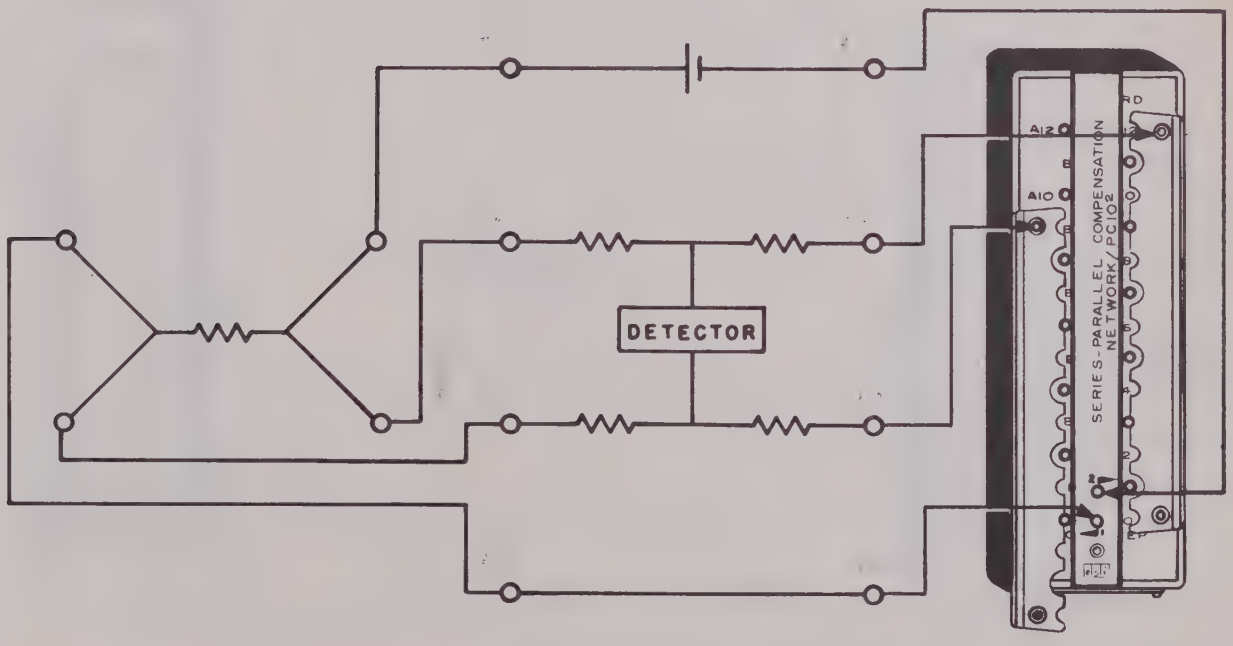


FIG. 4.3.1a

4) Compare the two resistances by the interchange method described in Section 2.3.2, also see the suggestions given in Section 2.3.3.

This gives the deviation of the one ohm per step SR 1010 from the standard, to find its deviation from nominal add to this the deviation from nominal of the one ohm standard.

5) Connect the Thomas pattern one ohm standard to the standard terminals of the bridge.

See Figure 4.3.1b.

6) Connect ten resistors of the ten ohm per step box in parallel using the parallel compensation network and shorting bars.

See Section 2.2.2 for proper parallel connections.

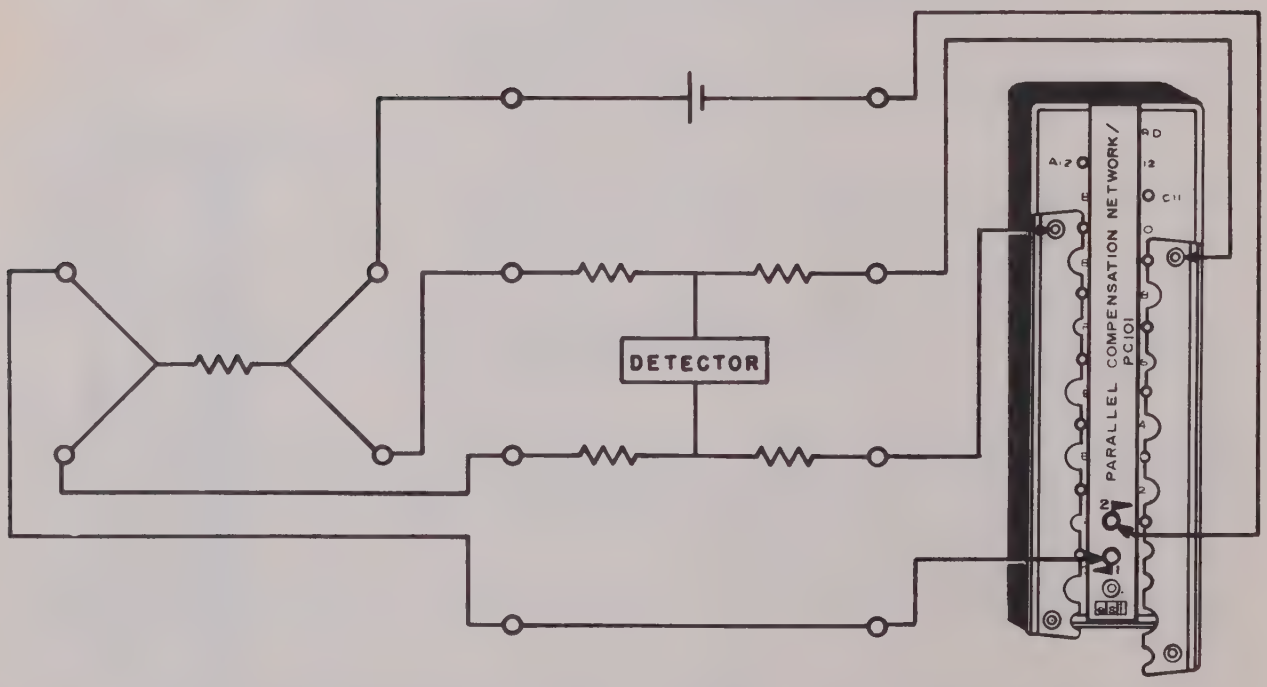


FIG. 4.3.1b

7) Connect the ten parallel resistors of the ten ohm per step box to the unknown terminals of the bridge.

See Figure 4.3.1b.

8) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the ten ohm per step SR 1010 from the standard, to find its deviation from nominal add to this the deviation from nominal of the one ohm standard.

9) Remove the parallel straps from the ten ohm per step box and connect the same ten resistors in series to the standard terminals of the bridge.

See Figure 4.3.1c.

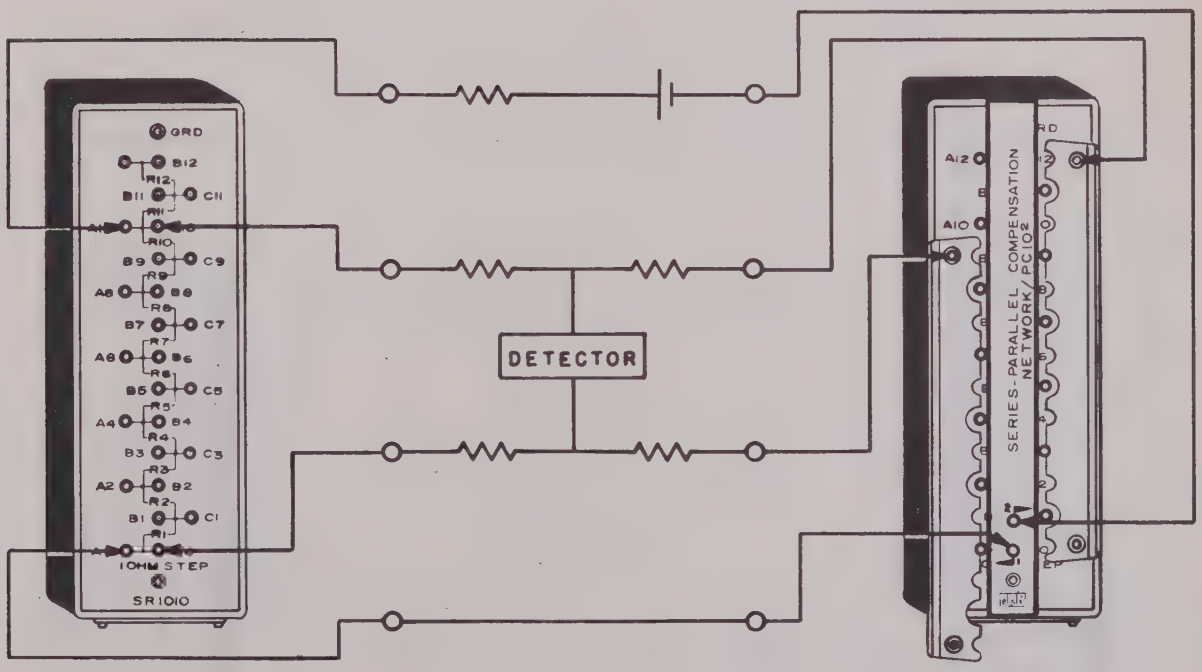


FIG. 4.3.1c

10) Connect nine resistors of the 100 ohm per step box in series-parallel using the compensation network and connect to the unknown terminals of the bridge.

See Section 2.2.3 for proper series-parallel connections and Figure 4.3.1c for connections to bridge.

11) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the one hundred ohm per step box from the ten ohm per step box, to find its deviation from nominal add to this the deviation from nominal of the ten ohm per step box as determined in step 8 above.

12) Connect the ten series connected resistors of the ten ohm per step box to the standard terminals of the bridge.

See Figure 4.3.1d.

13) Connect ten resistors of the one kilohm per step box in parallel and connect to the unknown terminals of the bridge.

See Figure 4.3.1d.

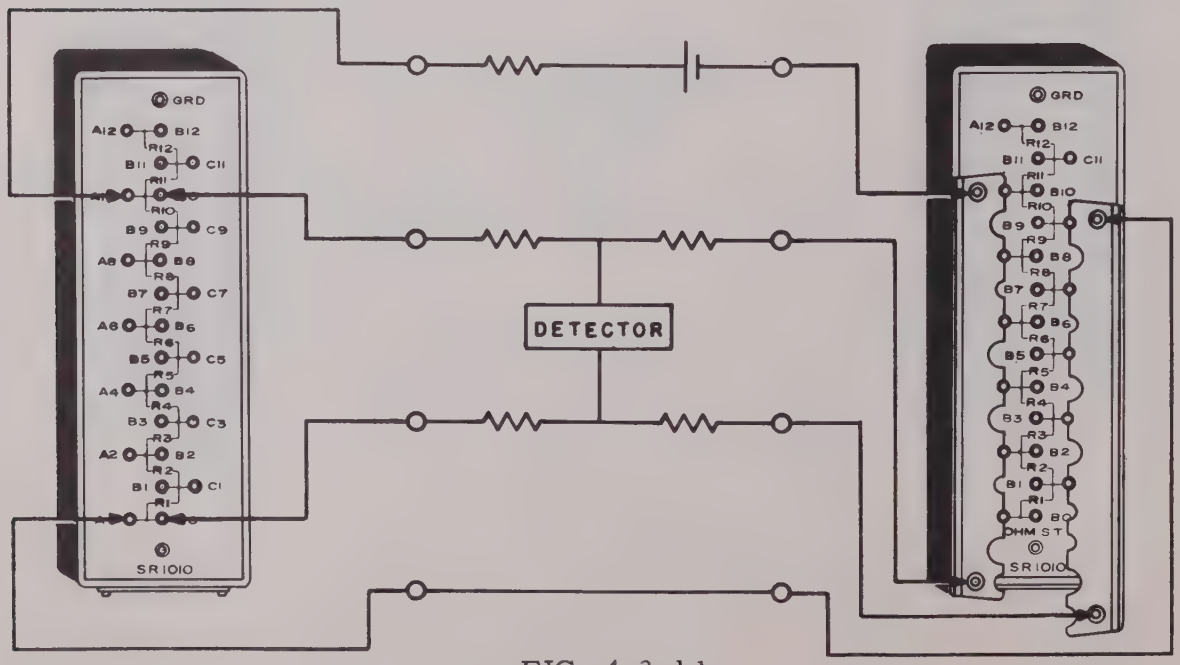


FIG. 4.3.1d

14) Compare the two resistances by the interchange method described in Section 2.3.2.

This gives the deviation of the one kilohm per step box from the ten ohm per step box, to find its deviation from nominal add to this the deviation from nominal of the ten ohm per step box as determined in step 8 above.

15) Remove the parallel straps from the one kilohm per step box and connect the same ten resistors in series to the standard terminals of the bridge.

See Figure 4.3.1e.

16) Connect nine resistors of the ten kilohm per step box in series-parallel and connect to the unknown terminals of the bridge.

See Figure 4.3.1e.

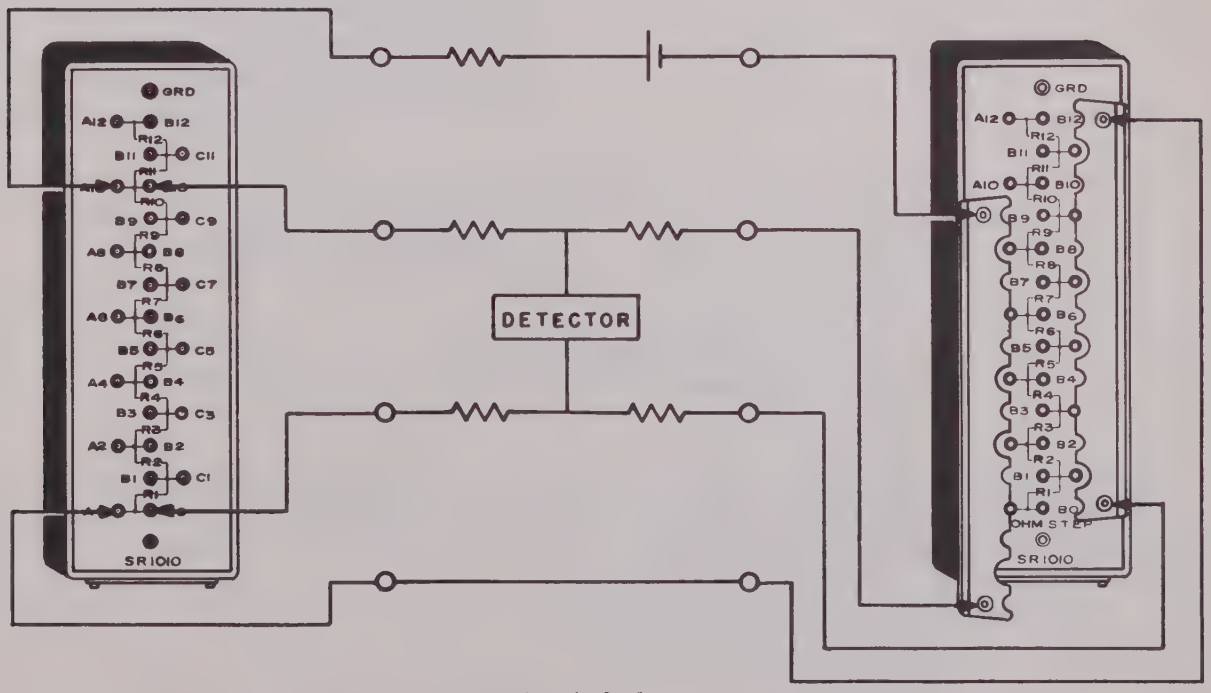


FIG. 4.3.1e

17)	Compare the two resistances by the interchange method described in Section 2.3.2.	This gives the deviation of the ten kilohm per step box from the one kilohm per step box, to find its deviation from nominal add to this the deviation from nominal of the one kilohm per step box as determined in step 14 above.
18)	Connect the ten series connected one kilohm resistors to the standard terminals of the bridge.	See Figure 4.3.1d.
19)	Connect ten resistors of the one hundred kilohm per step box in parallel and connect to the unknown terminals of the bridge.	See Figure 4.3.1d.
20)	Compare the two resistances by the interchange method described in Section 2.3.2.	This gives the deviation of the one hundred kilohm per step box from the one kilohm per step box, to find its deviation from nominal add to this the deviation from nominal of the one kilohm per step box as determined in step 14 above.

4.3.2 CALIBRATION OF INDIVIDUAL RESISTORS

1)	Connect the Thomas pattern one ohm standard to the standard terminals of the bridge.	
2)	Beginning with the first resistor of the one ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.	See Figure 4.3.3 Column A.

3)	Calculate the average deviation, from the above, for the first nine resistors.	See Section 4.3.3.
4)	Subtract this average value from the measured value of step 4, Section 4.3.1.	
5)	Add this difference to each of the individual deviations measured above.	This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.
6)	Connect the first ten resistors of the one ohm per step box in series to the standard terminals of the bridge.	
7)	Beginning with the first resistor of the ten ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.	
8)	Calculate the average deviation from the above for the first ten resistors.	
9)	Subtract this average value from the measured value of step 8, Section 4.3.1.	
10)	Add this difference to each of the individual deviations measured above.	This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

11) Connect the first ten resistors of the ten ohm per step box in series to the standard terminals of the bridge.

12) Beginning with the first resistor of the one hundred ohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

13) Calculate the average deviation from the above for the first nine resistors.

14) Subtract this average value from the measured value of step 11, Section 4.3.1.

15) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

16) Connect the first ten resistors of the one hundred ohm per step box in series to the standard terminals of the bridge.

17) Beginning with the first resistor of the one kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

18) Calculate the average deviation from the above for the first ten resistors.

19) Subtract this average value from the measured value of step 14, Section 4.3.1.

20) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

21) Connect the first ten resistors of the one kilohm per step box in series to the standard terminals of the bridge.

22) Beginning with the first resistor of the ten kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

23) Calculate the average deviation from the above for the first nine resistors.

24) Subtract this average value from the measured value of step 17, Section 4.3.1.

25) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

26) Connect the first ten resistors of the ten kilohm per step box in series to the standard terminals of the bridge.

27) Beginning with the first resistor of the one hundred kilohm per step box, connect each resistor one at a time to the unknown terminals of the bridge and measure their deviation from the standard.

28) Calculate the average deviation from the above for the first ten resistors.

29) Subtract this average value from the measured value of step 20, Section 4.3.1.

30) Add this difference to each of the individual deviations measured above.

This will be the deviation from nominal of the individual resistors, and corresponds to the first column of the calibration card attached to the end of the SR 1010.

Compare these calibrated values with those on the chart at the end of the boxes. Before replacing this chart with one using the values just determined be sure that the standards and procedures used in the new calibration were sufficiently accurate. It is also recommended that the charts not be replaced unless two or more complete calibration sequences give the same answer, preferably when performed by different operators, and even using different bridges or ratio sets if available.

4.3.3 FILLING OUT THE CALIBRATION CARD

If it has been determined that the values given on the calibration card are no longer correct the following procedure is recommended for filling out a new card.

1)	List the deviation from nominal of the individual resistors as measured in Section 4.3.2.	See Figure 4.3.3 Column A.
2)	Calculate the group average from these deviations corresponding to the group average measured in Section 4.3.1.	This group will consist of the first nine resistors for the 1 ohm, 100 ohm and 10 kilohm per step boxes and the first ten resistors for the 10 ohm, 1 kilohm and 100 kilohm per step boxes.
3)	Subtract the calculated average from the measured average to obtain the correction for the measured individual deviations.	
4)	Add the above correction to each of the measured individual deviations.	See Figure 4.3.3 Column B.
5)	Sum up each of the individual deviations from the first down to each of the subsequent deviations. For example, the cumulative sum corresponding to R4 will be the sum of the deviations of R1, R2, R3, and R4.	See Figure 4.3.3 Column C.
6)	Divide each of the cumulative sums by the number of deviations involved in the sum. For example, the cumulative sum corresponding to R4 will be divided by four.	See Figure 4.3.3 Column D.
7)	Round off the corrected individual deviations to the nearest ppm and fill in the first column of the calibration chart (labeled Individual (ppm)) with these values.	See Figure 4.3.3 sample calibration chart.

8) Round off the cumulative averages to the nearest ppm and fill in the second column of the calibration chart (labeled Cumulative (ppm)) with these values.

See Figure 4.3.3 sample calibration chart.

	A Measured Individual Deviations (From Section 4.3.2)	B Corrected Individual Deviations	C Cumulative Sum	D Cumulative Average
R1	+3.6	+2.1	+2.1	+2.1
R2	+5.7	+4.2	+6.3	+3.2
R3	+0.3	-1.2	+5.1	+1.7
R4	+5.3	+3.8	+8.9	+2.2
R5	-1.6	-3.1	+5.8	+1.2
R6	+4.9	+3.4	+9.2	+1.5
R7	+4.5	+3.0	+12.2	+1.7
R8	-3.2	-4.7	+7.5	+0.9
R9	+4.0	+2.5	+10.0	+1.1
R10	+6.6	+5.1	+15.1	+1.5
R11	+3.2	+1.7	+16.8	+1.5
R12	-2.7	-4.2	+12.6	+1.0

9 | 23.5 Sum
2.6 Average

Measured group average for nine resistors (From Section 4.3.1) = +1.1

Minus group average calculated from measured individual deviations = -2.6

Correction to be added to measured individual deviations = -1.5

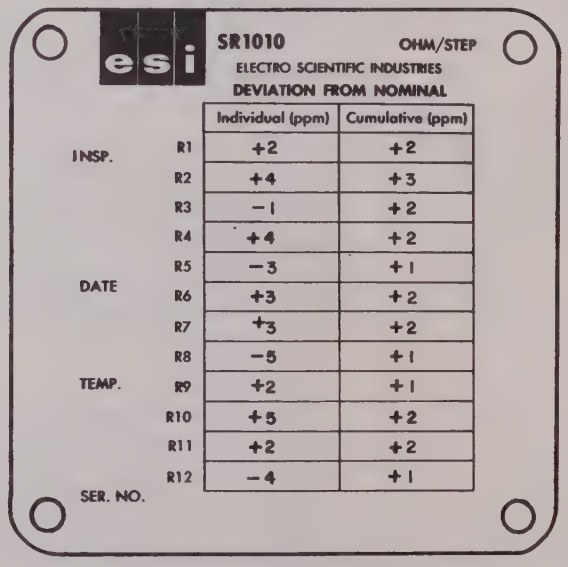


FIG. 4.3.3

4.4 SPECIAL TESTS

4.4.1 JUNCTION TRANSRESISTANCE

An essential characteristic of the ESI MODEL SR 1010 TRANSFER STANDARDS is the low resistance of the junction between the resistors and the binding posts (less than one microhm). If the junction transresistance is too high, the transfer accuracy of the units will be impaired.

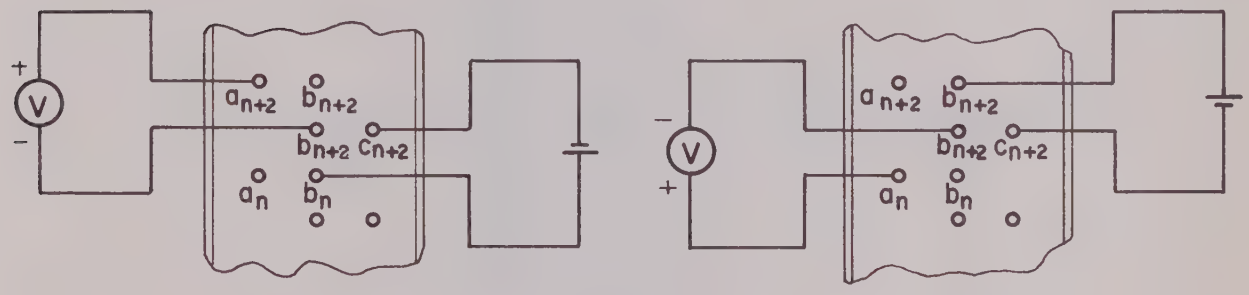
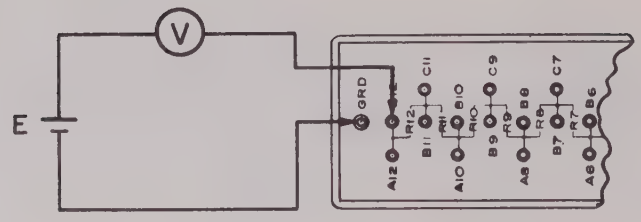


FIG. 4.4.1

The method of checking the junction transresistance is illustrated in Figure 4.4.1. By using a current source of one amp and a microvoltmeter capable of seeing one tenth of a microvolt the junction resistance can be measured to a tenth of a microhm. The transresistance measured by both the circuits shown and their difference should be less than 1/2 microhm. This test need be made on the one ohm per step and ten ohm per step boxes only, since the resistance of the junction material is too small to cause as much as one ppm error in a one hundred ohm per step box.

4.4.2 INSULATION RESISTANCE



The circuit for measuring the leakage resistance of the SR 1010 is illustrated in Figure 4.4.2. The leakage resistance is:

$$R_L = \frac{ER_M}{V}$$

where:

R_L is the leakage resistance from all terminals in parallel to ground in ohms.
E is the supply voltage in volts.
R_M is the input resistance of the meter.
V is the reading of the voltmeter.

R_L should be greater than 10^{12} ohms.

4.4.3 FOUR-TERMINAL PARALLELING ACCURACY OF THE SYSTEM

The uncertainty due to connection resistances of four terminal resistors in parallel is less than:

$$\pm 2\left(\frac{r}{R}\right)(d_{CR} - d_R)$$

where:

r is the greatest bus bar resistance.
R is the nominal value of the resistors being paralleled.
$(d_{CR} - d_R)$ is the greatest bridge unbalance in terms of the compensation resistors and the resistors being connected.

The values of $\frac{r}{R}$ and $(d_{CR} - d_R)$ can be measured to find the expected accuracy of a particular connection.

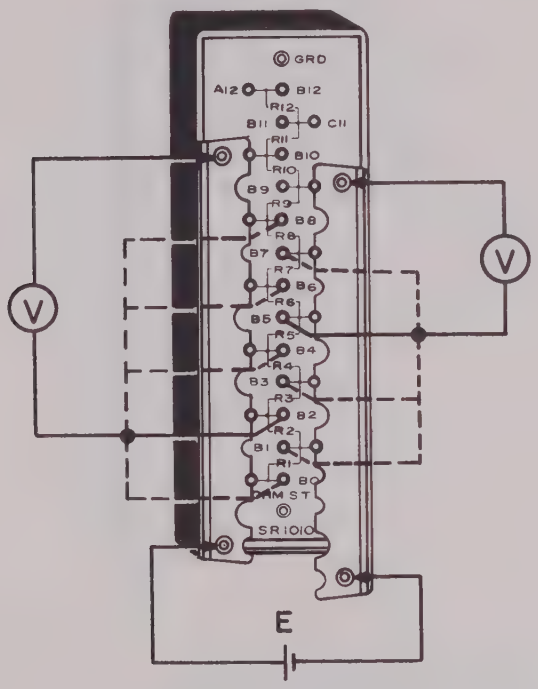


FIG. 4.4.3a

The value of $\frac{r}{R}$ can be found by measuring the voltage drops from a point on the bus bars to the junction of adjacent resistors, shown in Figure 4.4.3a.

1) Connect the shorting bar.
2) Measure voltage from a point on the bars to the unused terminals, this is the voltage to the junction of adjacent resistors.
3) Find the maximum difference of values V for each bar.
4) Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\frac{V_{max} - V_{min}}{E} = (\frac{r}{R})_{max}$$

The bridge unbalance can be measured as shown in Figure 4.4.3b. The measured values can be multiplied together and doubled to give an upper bound of the connection error. This usually includes a very substantial safety factor.

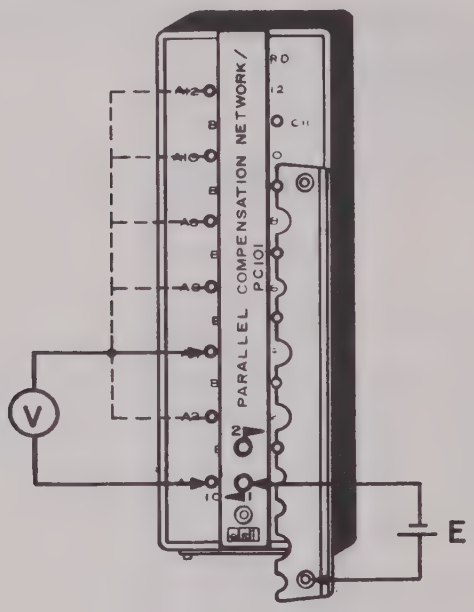


FIG. 4.4.3b

1) Connect one shorting bar.
2) Connect the compensating network.
3) Supply a voltage E from the shorting bar to the other side of the network.
4) Measure the voltage V from one unused shorting bar terminal to each of the others.
5) Change the shorting bar to the other side and repeat.
6) Find the maximum voltage difference $(V_{max} - V_{min})$ between terminals.
7) Calculate $(d_{CR} - d_R)_{max}$

$$\left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2R_0}{R} + \frac{R}{R_0}\right) = (d_{CR} - d_R)_{max}$$

4.4.4 FOUR-TERMINAL SERIES-PARALLELING ACCURACY OF THE SYSTEM

The determination of the four-terminal series-parallel accuracy is the same as that of the four-terminal parallel accuracy described in Section 4.4.3. See Figure 4.4.4a for measuring $\frac{r}{R}$ and 4.4.4b for measuring $(d_{CR} - d_R)$.

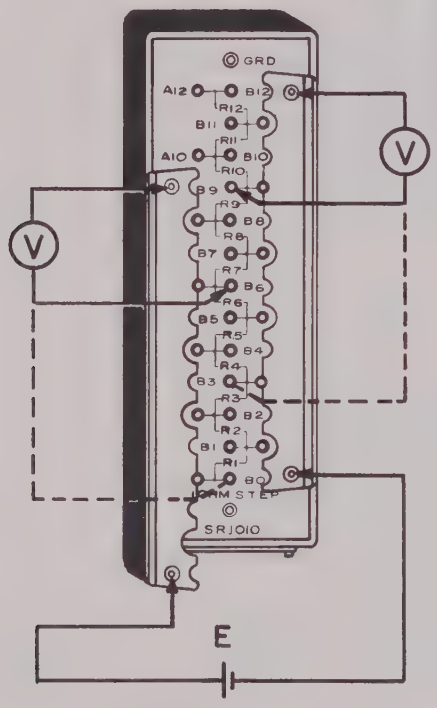


FIG. 4.4.4a

1) Connect the shorting bars.
2) Measure the voltage from a point on the bars to the terminals that would normally be connected to the compensation network.
3) Find the maximum difference of values V for each bar.
4) Use the greatest V difference to calculate $(\frac{r}{R})_{max}$

$$\frac{V_{max} - V_{min}}{E} = (\frac{r}{R})_{max}$$

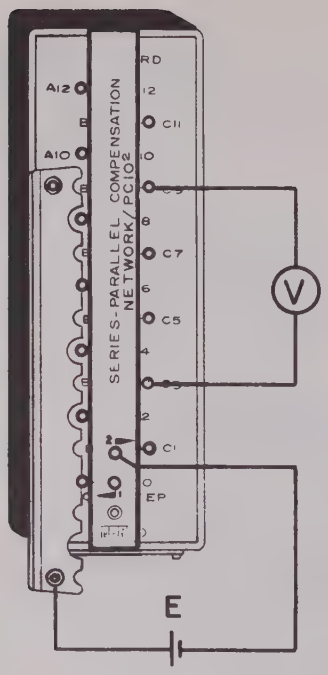


FIG. 4.4.4b

1) Connect the shorting bar.
2) Connect the compensation network.
3) Supply a voltage E from the shorting bar to the other side of the network.
4) Measure the voltage between the terminal normally connected to the missing shorting bar.
5) Change the shorting bar to the other side and repeat.
6) Calculate $(d_{CR} - d_R)_{max}$.

$$(d_{CR} - d_R) = \left(\frac{V_{max} - V_{min}}{E}\right)\left(2 + \frac{2CR}{3R} + \frac{3R}{CR}\right)$$

where:

R is the nominal value of the resistors of the SR 1010.
CR is the nominal value of the resistors in the compensation network.

SECTION V

PARTS LIST

Manufacturer of the part is given in a code number according to the Federal Supply Code for Manufacturers; see list of manufacturers below. Parts recommended as spares to sustain operation in isolated locations are indicated in the recommended spare parts column.

Parts manufactured by Electro Scientific Industries must be ordered from the factory. When ordering parts from the factory include the following information:

Model and serial number of the instrument
Electro Scientific Industries part number
Circuit reference designator
Description of part

CODE LIST OF MANUFACTURERS

11702	SYRACUSE RUBBER PRODUCTS COMPANY Syracuse, New York
11837	ELECTRO SCIENTIFIC INDUSTRIES Portland, Oregon

Description	Mfr	ESI Part No.	Qty Used	Recm SP
Cap, Binding Post, Metal	11837	1172	2	2
Cap, Binding Post, Ins.	11837	1170	26	12
Bumper, Rubber Mfr PN M-266	11702	8220	4	2
Holder, Card	11837	8535	1	1
Card, Calibration	11837	8536	1	5

Electro Scientific Industries, Inc.

13900 N. W. SCIENCE PARK DRIVE
PORTLAND, OREGON 97229
(area code 503) 646-4141 • telex: 036-600
cable address: ESIACTION

WARRANTY OF TRACEABILITY

THE REFERENCE STANDARDS OF MEASUREMENT OF ELECTRO SCIENTIFIC INDUSTRIES INC. ARE COMPARED WITH THE U.S. NATIONAL STANDARDS THROUGH FREQUENT TESTS BY THE U.S. NATIONAL BUREAU OF STANDARDS.

THE ESI WORKING STANDARDS AND TESTING APPARATUS USED ARE CALIBRATED AGAINST THE REFERENCE STANDARDS IN A RIGOROUSLY MAINTAINED PROGRAM OF MEASUREMENT CONTROL.

THE MANUFACTURE AND FINAL CALIBRATION OF THIS INSTRUMENT WERE CONTROLLED BY THE USE OF THE ESI REFERENCE AND WORKING STANDARDS AND TESTING APPARATUS IN ACCORDANCE WITH ESTABLISHED PROCEDURES AND WITH DOCUMENTED RESULTS. (REFERENCE MIL-C-45662)

ESI
PART NO1866

Electro Scientific Industries, Inc.

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PORTLAND, OREGON 97229
(area code 503) 646-4141 • telex: 036-600
cable address: ESIACTION

WARRANTY OF QUALITY

ELECTRO SCIENTIFIC INDUSTRIES,INC. WARRANTS ITS PRODUCTS TO BE FREE FROM DEFECTS IN MATERIAL AND WORKMANSHIP. FOR A PERIOD OF TWO YEARS FROM THE DATE OF SHIPMENT TO THE ORIGINAL PURCHASER, WE WILL SERVICE OR, AT OUR OPTION, REPLACE ANY DEVICE WHICH FAILS IN NORMAL USE TO MEET ITS PUBLISHED SPECIFICATIONS.

BATTERIES AND TUBES WHICH HAVE GIVEN NORMAL SERVICE ARE EXCEPTED.

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JANUARY 1964
REPLACES JUNE 1962

COMMENTS ON USING ESI MODEL SR 1010 RESISTANCE TRANSFER BOXES FOR TRANSFERRING FROM A THOMAS-TYPE ONE OHM RESISTOR

1) Mount the Thomas-Type one ohm standard resistor in a small unstirred pot of oil. Use a thermometer with 0.1C° resolution to observe the oil temperature.	The purpose of this bath is to assist in the accurate determination of the temperature of the standard resistor. The standard resistor need not be kept at an exact temperature, but it is necessary to know its temperature to ± 0.1°C. The oil will also provide enough thermal lag to allow measurement of the resistor to at least two ppm when the full output of the 800R Generator is used to get adequate sensitivity.
2) Null the bridge in as short a time as possible.	This will avoid errors caused by heating the resistors. A good practice would be to come to an initial null with low bridge power before stepping up the power (and sensitivity) for the final null.
3) Accomplish the transfer from the parallel to the series or series-parallel connection of the SR-1010 boxes in as short a time as possible.	This will avoid errors caused by room temperature changes. When the SR 1010's are used for transferring, their exact temperature is of little consequence, but they must be at the same temperature during the procedure so that the various connections of the boxes will have the same value.

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Electro Scientific Industries
13900 N.W. SCIENCE PARK DRIVE • PORTLAND, OREGON 97229
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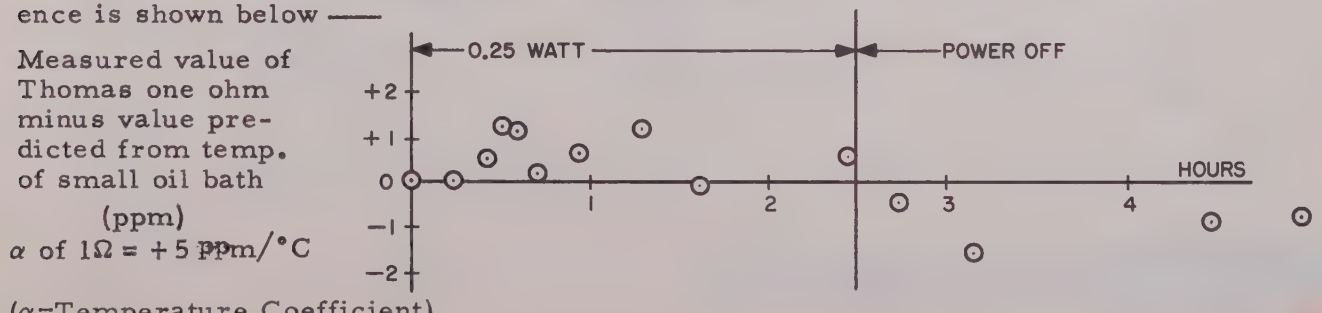
POWER COEFFICIENT OF THOMAS-TYPE ONE OHM STANDARD RESISTOR

When using the ESI Model 242 Kelvin Resistance Bridge to intercompare one ohm resistors, there is a problem with sensitivity caused by the fact that the bridge and its detector were chosen to cover a wide range of resistance and are not perfectly matched for one ohm intercomparisons. In order to accomplish one ppm work at the one ohm level, it is necessary to use the full output of the 800R Generator. When intercomparing a one ohm standard resistor and a 10 ohm per step SR 1010 box connected in parallel, the one ohm resistor will be dissipating about 0.25 watts (measured in an actual setup).

How closely will the temperature of an oil bath and temperature-coefficient of a Thomas type one ohm standard resistor predict the resistance of the resistor? A Thomas-Type one ohm standard resistor was mounted in a small, occasionally stirred (when the thermometer was read) oil bath. The one ohm standard was intercompared to a 10 ohm per step SR 1010 box connected in parallel that was mounted in a large bath of oil. The SR 1010 was thought to have a lower power coefficient than the one ohm resistor because it consisted of a large amount of manganin wire in direct contact with the oil (except for a thin coat of varnish). The two resistors were intercompared with a 242 bridge with a continuous 0.25 watts dissipated in the one ohm resistor. The temperature of both resistors was observed.

In this experiment the data of most interest was the measured difference between the two resistors and the calculated difference expected because of the temperatures of the oil baths. The difference between these two figures would indicate how well the temperature of the oil bath would predict the value of the one ohm resistor when it was dissipating 0.25 watts continuously. This difference is shown below ——



Some of the erratic nature of the points is probably caused by the fact the bridge used was subject to room temperature variations and had limited resolution.

This data indicates that it is possible to measure a Thomas-Type one ohm standard resistor on an ESI Model 242 Resistance Bridge to one ppm (using the full power output of the 800).

A conversation with Dr. Thomas of the NBS indicated that the one ohm resistor will not be harmed by power levels as high as one watt. This agrees with the comments of Wenner's 1940 paper on resistance comparisons.

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esi® Engineering Bulletin

GENERAL

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INTERNATIONAL SYSTEM OF UNITS

Quantity	*Unit*	*Symbol*	
	Elemental units		
Length	meter	m	
Mass	kilogram	kg	
Time	second	s	
Electric current	ampere	A	
Temperature	degree Kelvin	°K	
Luminous intensity	candela	cd	
	Supplementary Units		
Plane angle	radian	rad	
Solid angle	steradian	sr	
	Derived Units		
Area	square meter	m^2	
Volume	cubic meter	m^3	
Frequency	hertz	Hz	(s^{-1})
Density	kilogram per cubic meter	kg/m^3	
Velocity	meter per second	m/s	
Angular velocity	radian per second	rad/s	
Acceleration	meter per second squared	m/s^2	
Angular acceleration	radian per second squared	rad/s^2	
Force	newton	N	$(kg \cdot m/s^2)$
Pressure	newton per sq meter	N/m^2	
Kinematic viscosity	sq meter per second	m^2/s	
Dynamic viscosity	newton-second per sq meter	$N \cdot s/m^2$	
Work, energy, quantity of heat	joule	J	$(N \cdot m)$
Power	watt	W	(J/s)
Electric charge	coulomb	C	$(A \cdot s)$
Voltage, potential difference, electromotive force	volt	V	(W/A)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	$(A \cdot s/V)$
Magnetic flux	weber	Wb	$(V \cdot s)$
Inductance	henry	H	$(V \cdot s/A)$
Magnetic flux density	tesla	T	(Wb/m^2)
Magnetic field strength	ampere per meter	A/m	
Magnetomotive force	ampere	A	
Luminous flux	lumen	lm	$(cd \cdot sr)$
Luminance	candela per sq meter	cd/m^2	
Illumination	lux	lx	(lm/m^2)

NBS Technical News Bulletin
April 1964

LITHO IN U.S.A.

esi

TO FACILITATE the exchange of scientific data, the Bureau has adopted the International System of Units for use by its staff. Henceforth the Bureau will employ this system of units in all its publications except where use of these units would obviously impair communication or would reduce the usefulness of a report to the primary recipients. Standards and measuring devices whose nominal values are in customary U.S. units, like inches, pounds, and gallons, will continue to be calibrated in terms of those units.

The International System of Units (designated SI, for *Systeme International d'Unités*) was defined and given official status in a resolution of the 11th General Conference on Weights and Measures which met in Paris in October 1960.[1] The SI is based on the elemental units. Of these units, those for mass, length, time, and temperature are independent; that is, a definition of one does not depend on definitions of the others. However, the ampere and the candela involve other units in their definitions.

In the International System there is one and only one unit for each quantity, although multiples and submultiples of each unit may be designated by the prefixes approved by the 11th General Conference on Weights and Measures.

[1] Actions of the 11th General Conference on Weights and Measures, *NBS Tech. News Bull.* **44**, *199 (1960)*.

SI PREFIXES

Multiples and Submultiples	*Prefixes*	*Symbols*	*Pronunciations*
10^{12}	tera	T	tĕr′ȧ
10^{9}	giga	G	jĭ′ gȧ
10^{6}	mega	M	mĕg′ȧ
10^{3}	kilo	k	kĭl′ō
10^{2}	hecto	h	hĕk′tō
10	deka	da	dĕk′ȧ
10^{-1}	deci	d	dĕs′ĭ
10^{-2}	centi	c	sĕn′tĭ
10^{-3}	milli	m	mĭl ĭ
10^{-6}	micro	μ	mī′ krō
10^{-9}	nano	n	năn′ō
10^{-12}	pico	p	pē′ cō
10^{-15}	femto	f	fĕm′ tō
10^{-18}	atto	a	ăt′ tō

CONVENIENT AUDIO FREQUENCY UNITS

For measurement and calculation in the audio frequency range the conventional electrical units are often inconvenient. A consistent set of units can be chosen so that the numerical values commonly encountered will be more practical while at the same time the equations used in calculations will not require any troublesome conversion constants. If either set of units listed below is followed consistently, the equations used for calculations will be unaltered. For example, E = IR holds true equally well with E in volts, I in amperes, and R in ohms; or with E in volts, I in milliamperes and R in kilohms.

FUNCTION	CONVENTIONAL UNITS	CONVENIENT AUDIO FREQUENCY UNITS
ω	radian/s = $2\pi f_{Hz}$	kiloradian/s = $2\pi f_{kHz}$
f	hertz	kilohertz
t	second	millisecond
C	farad	microfarad
Z, R and X	ohm	kilohm
L	henry	henry
I	ampere	milliamp
E	volt	volt
P	watt	milliwatt
Q and D	per unit ratio	per unit ratio

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AN IMPROVED TECHNIQUE FOR ESTABLISHING RESISTANCE RATIOS

by
R. M. Pailthorp and J. C. Riley

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INSTRUMENT-AUTOMATION CONFERENCE AND EXHIBIT
NEW YORK CITY OCTOBER 15-18, 1962

LITHO IN U.S.A.

AN IMPROVED TECHNIQUE FOR ESTABLISHING RESISTANCE RATIOS

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Research and Development Project Engineer
Jack Riley
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ABSTRACT

A previously disclosed but seldom used application of four-terminal resistors permanently connected in series is discussed. Techniques for obtaining accurate ratios by four-terminal series, parallel, and series-parallel connections are analyzed.

THE IMPORTANCE OF RESISTANCE RATIOS

One of the most important functions of a dc standards laboratory is the establishment of resistance ratios. The intercomparison of resistors, voltages, and currents and the calibration of most dc measuring equipment depends on the accuracy of these ratios. For instance, the legal value of the ohm is maintained at the National Bureau of Standards by means of a group of Thomas-type one-ohm standard resistors. Other resistance values are referenced to one ohm by using resistance ratio techniques. Even the intercomparison of these standards depends on an accurate determination of a one-to-one ratio.

WHERE TO ESTABLISH RESISTANCE RATIOS

Resistance ratios do not involve the unit of resistance. They can be accurately determined by any laboratory with proper equipment and technique. Of even greater importance, if highest accuracy is desired, each laboratory can establish the ratios at the time and place they are needed in order to minimize the effects of time, temperature, shipment, etc.

TWO-TERMINAL BUILD-UP RESISTORS

Resistance ratios can be established by the use of build-up resistors. Build-up resistors can be connected in series, parallel, or series-parallel combinations to establish desired ratios. One accurate ratio technique using build-up resistors is the calibration of a ratio device by the use of r plus n nominally equal two-terminal resistors. If r nominally equal resistors are combined (connected in series, parallel, or series-parallel) in one arm of a bridge and n resistors of the same nominal value are combined in the other arm, and the resistors are rotated in a cyclic order until each resistor occupies each position once, the average of the r plus n readings is the reading that would be obtained if all the resistors were equal. The ratios that may be established by this technique are limited only by one's ability to find the proper build-up resistor combinations and perserverance in taking the necessary r plus n readings. The most used and useful ratios are 1:1 and 1:10. Usually the build-up resistors are used to calibrate a ratio bridge, and the calibrated bridge is used to transfer from one resistor value to another.

If two-terminal build-up resistors are used they must be high enough in value to avoid problems caused by connection and lead resistances. For highest accuracy, resistors that are at least 100 ohms are required, especially for parallel connections.

USING FOUR-TERMINAL BUILD-UP RESISTORS

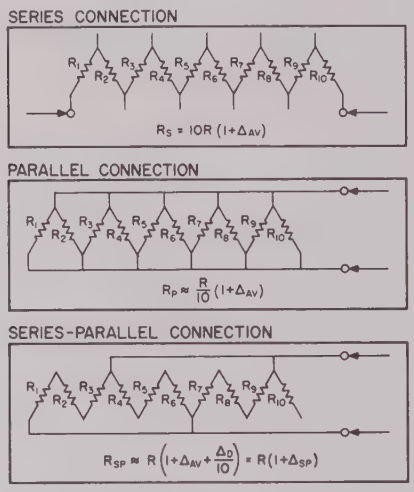
The remainder of this paper discusses ratio techniques using four-terminal build-up resistors.

Hamon (1) has shown how four-terminal resistors can be connected in series, parallel, or series-parallel. The resistors are permanently connected in series, but ten of them may be connected in parallel, or nine of them may be connected in series-parallel. Other combinations are possible, but these are the most useful for ten to one and one hundred to one ratios. A two-terminal representation of the connections, and the connected resistance values are shown in Figure 1.

The advantage of this technique can be seen from the similarity between the formulae in Figure 1. For instance, if one knows the value of the ten resistors in the parallel connection, the the value of the same resistors in the series

Numbers in parentheses refer to similarly numbered references at the end of this paper.

connection is also known and one intercomparison, to find Δ_D, will give the value of the first nine resistors connected in series-parallel. These connections can be used for low resistance values too if similar four-terminal connections can be made accurately.



Where R_i = nominal resistance of the ith resistor
Δ_i = deviation of R_i from R $\quad R_i = R(1+\Delta_i)$
R_S = resistance of 10 resistors in series
R_P = resistance of 10 resistors in parallel
R_{SP} = resistance of 9 resistors in series-parallel
Δ_{AV} = average deviation of the 10 resistors $\quad \Delta_{AV} = \frac{1}{10}\sum_{i=1}^{10}\Delta_i$
Δ_D = deviation of R_{SP} from the tenth resistor R_{10}
Δ_{SP} = deviation of R_{SP} from R $\quad \Delta_{SP} = \left(\Delta_{AV}+\frac{\Delta_D}{10}\right)$

These formulas are correct to about $\pm\left(\frac{1}{10}\sum_{i=1}^{10}\Delta_i^2 - \Delta_{AV}^2\right)$ (±1ppm if the build-up resistors are accurate to ±0.1% and there are no connection errors)

FIGURE 1. BUILD-UP RESISTOR CONFIGURATION

Figure 2 shows how three build-up resistor sets can be used to transfer from one ohm to all of the decade values up to one megohm using only one-to-one comparisons.

MEASUREMENT NUMBER	STANDARD RESISTOR	RESISTANCE LEVEL OF INTERCOMPARISON	UNKNOWN RESISTOR
1	1Ω (NBS certified)	1Ω	measure Δ_{AV} of ten 10Ω's in parallel
2	ten 10Ω's in series	100Ω	measure Δ_{AV} of ten 1k's in parallel
3	ten 1k's in series	10k	measure Δ_{AV} of ten 100k's in parallel
4	tenth (R_{10}) 10Ω	10Ω	measure Δ_D of nine 10Ω's in series-parallel, calculate Δ_{SP}
5	tenth (R_{10}) 1k	1k	measure Δ_D of nine 1k's in series-parallel, calculate Δ_{SP}
6	tenth (R_{10}) 100k	100k	measure Δ_D of nine 100k's in series-parallel, calculate Δ_{SP}

FIGURE 2. MEASUREMENTS (1:1 COMPARISONS) NECESSARY TO ESTABLISH STANDARDS OF RESISTANCE FOR THE SIX DECADE VALUES ABOVE 1Ω. CONNECTING TEN 100k'S IN SERIES GIVES THE 1 MEGOHM STANDARD

Some features of the resistance transfer technique described in Figure 2 are:

1. All of the required measurements are intercomparisons of nominally equal resistors that can be accomplished easily and accurately by a simple interchange or substitution. The bridge used must be stable during the time it takes to make one intercomparison and must have adequate resolution, sensitivity, and repeatability.
2. Only one intercomparison per decade of transfer is needed, and it is possible to transfer two decades per intercomparison if all of the decade values are not needed.
3. Some (measurements 4 through 6 in Figure 2) of the measurements are relatively non-critical. The measured deviation Δ_D is divided by ten when it is used.
4. The series-parallel standard can be used to calibrate a bridge for measurement of the individual resistors of itself. The series combinations of these resistors gives calibrated integer values for the calibration of non-decade valued resistors. To establish standards at integer values for all decades, build-up resistors of each decade value are required. The calibrated resistors can also be used as a voltage divider standard to calibrate Kelvin-Varley dividers, etc. (4)
5. The accuracy of the transfer technique depends on the short-term stability of the build-up resistors and does not require resistors of high long-term stability or known history.
6. If the build-up resistors do have good long-term stability, they can also be used for secondary standards of resistance and ratio in the time interval between calibrations.
7. The equipment used in the technique can be easily checked to determine the measurement accuracy.

ERROR REDUCTION

The remainder of this paper is an error analysis for four-terminal build-up resistor measurements.

The error sources to be considered are:

1. Resistor stability with changes in:
   a. Temperature
   b. Power
   c. Voltage
   d. Time
2. Junction, lead, and contact resistance effects

RESISTOR STABILITY

The time stability and ambient temperature coefficient for a build-up resistor are intimately connected. Both sources of error may be reduced by making a transfer in a short period of time. The average temperature of the build-up resistors is relatively unimportant, but changes in temperature during the transfer must be small to avoid significant changes in the resistor values. In practice, it is possible to measure the series, parallel, and series-parallel combinations in a time period of a few minutes. If commercially available low temperature coefficient resistors are mounted in a thermally lagged box, the short amount of time necessary to accomplish the measurements will keep the errors caused by temperature changes well below one ppm in a typical laboratory environment.

If wire-wound resistors are used for the build-up resistors, there will be no observable errors caused by voltage coefficient of the resistors.

The errors introduced by the power coefficients of the resistors may be reduced in two ways. One method is to keep the resistors at the same power level in all of the build-up configurations. The other is to operate the resistors at a low power level to avoid significant self-heating. The low power method is usually the most practical for the ten resistor technique. The power is always distributed between ten resistors in the series and parallel connections and nine resistors in the series-parallel connection. The only time a single resistor is used the measured deviation (Δ_D) is divided by ten (see Figure 2).

The power level which is used to avoid any short-term measurable resistance change resulting from self-heating may be higher than the power level which will result in a long-term observable resistance change. Since a resistor takes some time to heat after power is applied, the higher power level may be used if the resistors are measured in a short enough period of time.

FOUR-TERMINAL BUILD-UP RESISTORS IN SERIES

FIGURE 3. FOUR-TERMINAL BUILD-UP RESISTORS PERMANENTLY CONNECTED IN SERIES

The series configuration of the build-up resistors is shown in Figure 3. The four-terminal resistors can be measured individually or in any series combination. If the measured series resistance is to be equal to the sum of the individual resistor measurements, the junctions must have zero four-terminal resistance. The junction resistance is zero if a current source connected to any two of the four junction terminals produces zero voltage difference between the other two terminals.

In practice, the junctions do have some resistance. It is possible to make the resistance very low (much less than 1 microhm) by proper design. For instance, if four terminals are connected to a plane sheet of metal in the configuration shown in Figure 4, two of the terminals will always be on an equipotential line if a current source is connected to the other two terminals.

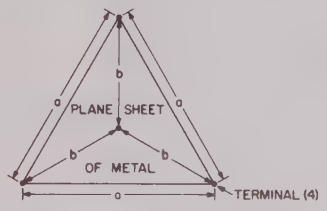


FIGURE 4. A FOUR-TERMINAL JUNCTION DESIGN

If the junction material has zero voltage coefficient and does not rectify current, a reasonable assumption for metals, Serles (2) has shown that the junction can be represented by the equivalent circuit shown in Figure 5. It is not

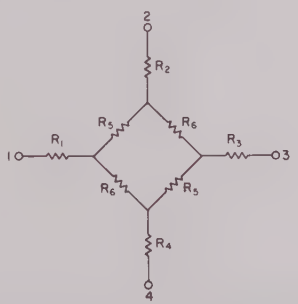


FIGURE 5. EQUIVALENT CIRCUIT OF FOUR-TERMINAL JUNCTION

convenient to measure the resistors shown in this equivalent circuit. A set of resistances that can be measured are shown in Figure 6. The resist-

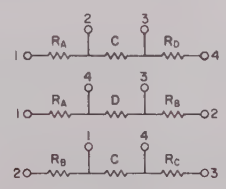


FIGURE 6. RESISTANCE MEASUREMENTS OF A FOUR-TERMINAL JUNCTION

ors shown in Figure 5 and 6 are related in the following manner.

$$R_1 = R_A - \sqrt{CD} \qquad R_A = R_1 + \frac{R_5 R_6}{2(R_5+R_6)}$$

$$R_2 = R_B - \sqrt{CD} \qquad R_B = R_2 + \frac{R_5 R_6}{2(R_5+R_6)}$$

$$R_3 = R_C - \sqrt{CD} \qquad R_C = R_3 + \frac{R_5 R_6}{2(R_5+R_6)}$$

$$R_4 = R_D - \sqrt{CD} \qquad R_D = R_4 + \frac{R_5 R_6}{2(R_5+R_6)}$$

$$R_5 = 2\left(D + \sqrt{CD}\right) \qquad C = \frac{R_6^2}{2(R_5+R_6)}$$

$$R_6 = 2\left(C + \sqrt{CD}\right) \qquad D = \frac{R_5^2}{2(R_5+R_6)}$$

Figure 7 shows the use of the equivalent circuit for the junction error when resistors are connected in series. If resistance R_{1234} is the

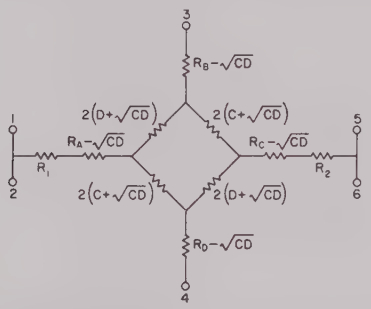


FIGURE 7. TWO FOUR-TERMINAL RESISTORS IN SERIES USING THE EQUIVALENT CIRCUIT FOR THE JUNCTION

notation for a four-terminal measurement defined by the ratio of the voltage drop from terminal 2 to terminal 3 to the current in terminal 1 and out terminal 4. The series error is the difference between the series measurement and the sum of the individual measurements.

SERIES ERROR FOR TWO RESISTORS

Series resistance error $= R_{2156} - R_{2134} - R_{4356} = C + D$

$$R_{2156} = \left(R_1 + R_A\right) + \left(C + D\right) + \left(R_2 + R_C\right)$$

$$R_{2134} = R_1 + R_A$$

$$R_{4356} = R_2 + R_C$$

SERIES ERROR FOR n RESISTORS

If C and D are less than $\pm M$, $(-M < C < +M$ and $-M < D < +M)$

For all junctions and $R_1 + R_A \approx R_2 + R_C \approx R$

Then $\quad -2M < (C+D) < +2M$

And $\quad$ series error $< \pm \frac{2M}{R} \times \frac{n-1}{n}$ in proportional parts

FOUR-TERMINAL BUILD-UP RESISTORS IN PARALLEL

There are two sources of errors to be considered when the four-terminal build-up resistors are connected in parallel and series-parallel. These are the errors arising from the junctions which connect the build-up resistors in series, and the errors arising from resistances of the leads and connections which complete the parallel circuit.

The circuit used in evaluating the junction errors is shown in Figure 8. The upper junction is evaluated assuming that the lower junction is perfect. The parallel error is the difference between the measured parallel resistance and the

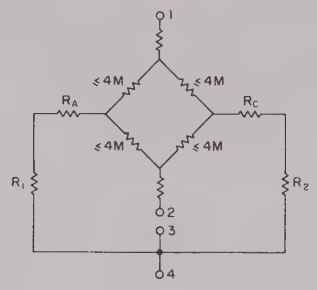


FIGURE 8. FOUR-TERMINAL RESISTORS IN PARALLEL USING THE EQUIVALENT CIRCUIT JUNCTION

parallel resistance computed from measurements of the individual resistors.

PARALLEL JUNCTION ERROR

$$-M \lesssim \left[R_{1234} - \frac{\left(R_1 + R_A\right)\left(R_2 + R_C\right)}{R_1 + R_A + R_2 + R_C} \right] \lesssim \pm M$$

M = limit of junction resistance $|C|$ and $|D| < M$

R_1 and $R_2 \approx R$

R_A, R_C, C and $D \ll R$

Figure 9 shows the equivalent circuit of two four-terminal resistors connected in parallel. R_1 and R_2 are the resistors to be measured and $R_3, R_4, \cdots R_{10}$ represent lead and connection resist-

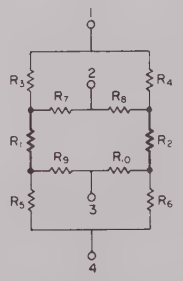


FIGURE 9. CIRCUIT USED TO CONSIDER LEAD AND CONNECTION ERRORS FOR TWO FOUR-TERMINAL RESISTORS IN PARALLEL

ances. Wenner (3) has shown that the measured resistance R_{1234} will be equal to the calculated parallel value of R_1 and R_2 if:

Either

$$\frac{R_1}{R_5} = \frac{R_2}{R_6} \quad \text{and} \quad \frac{R_1}{R_3} = \frac{R_2}{R_4}$$

Or

$$\frac{R_1}{R_7} = \frac{R_2}{R_8} \quad \text{and} \quad \frac{R_1}{R_9} = \frac{R_2}{R_{10}}$$

Or if

$$R_3 = R_4 = R_5 = R_6 = 0 \quad \text{or} \quad R_7 = R_8 = R_9 = R_{10} = 0$$

If these conditions are not met completely further analysis of the parallel connection of the resistors will yield the error Δ_P for the measured parallel resistance R_P in terms of the maximum ratio unbalance Δ_M and the maximum bus bar to build-up resistance ratio Q.

PARALLEL CONNECTION ERROR

$$R_P = \frac{R_1 R_2}{R_1 + R_2}\left(1 + \Delta_P\right)$$

Where Δ_P is:

$$\Delta_P < Q\,\Delta_M$$

When Δ_M is:

$$\Delta_1 , \Delta_2 < \Delta_M$$

For Δ_1 , Δ_2 of:

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}\left(1+\Delta_1\right) \qquad \frac{R_1}{R_5} = \frac{R_2}{R_6}\left(1+\Delta_2\right)$$

And Q is:

$$\frac{R_7 + R_8}{R_N} , \frac{R_9 + R_{10}}{R_N} < Q$$

For

$$R_1 \approx R_2 \approx R_N$$

In order to keep the error Δ_P low, both Q and Δ_M must be small. Q can be made small by reducing the resistances $R_7 + R_8$ and $R_9 + R_{10}$. Δ_M can be thought of as the maximum unbalance of two bridges. One is made up of the resistors R_1, R_2, R_3, and R_4 and the other bridge is made up of the resistors R_1, R_2, R_5, and R_6. Δ_M can result from lack of precision matching of the resistances $R_1, R_2, \cdots R_6$ or from uncertainty in the contact resistances when R_3, R_4, R_5, and R_6 are connected. The latter source of error can be reduced by making R_3, R_4, R_5, and R_6 large compared to the uncertainties in the contact resistances.

TEN FOUR-TERMINAL BUILD-UP RESISTORS IN PARALLEL

The parallel connection of the ten four-terminal build-up resistors is shown in Figure 10.

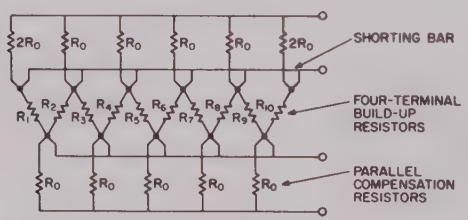


FIGURE 10. TEN FOUR-TERMINAL BUILD-UP RESISTORS IN PARALLEL

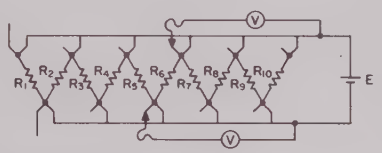
The shorting bars and the resistance from the junctions to the shorting bars are equivalent to the resistances R_7, R_8, R_9, R_{10} in Figure 9. These resistances should be small. The parallel-compensation resistors are equivalent to the resistances R_3, R_4, R_5, and R_6 in Figure 9. These resistances should be large compared to the uncertainty in the contact resistances when they are connected and should be proportional to the resistance of the build-up resistors. The two parallel-compensation resistors on the ends are double the others because they connect to one build-up resistor instead of two in parallel.

When several nominally equal resistors are connected in parallel the connection accuracy can be analyzed by assuming all of the compensation resistors except one are equal, and that all of the bus bar resistances except one are zero. At the same time all of the resistors being connected are assumed to be perfect except one. The three imperfect resistors all meet at one of the junctions. Since small first order error effects add linearly the results of this analysis can be extended to determine the connection accuracy. The connection uncertainty is less than:

$$\pm 2\left(\frac{r}{R}\right)\left(\Delta_{R_0} - \Delta_R\right)$$

Where
- r = greatest bus bar resistance
- R = nominal value of resistors being parallel connected
- $\left(\Delta_{R_0} - \Delta_R\right)$ = greatest bridge unbalance in terms of resistance deviations of the compensation resistors and the resistors being connected

The values of $\frac{r}{R}$ and $\left(\Delta_{R_0} - \Delta_R\right)$ can be measured to find the expected accuracy of a particular connection.



Connect the shorting bar

Measure voltage from a point on the bars to the unused terminals, this is the voltage to the junction of adjacent resistors

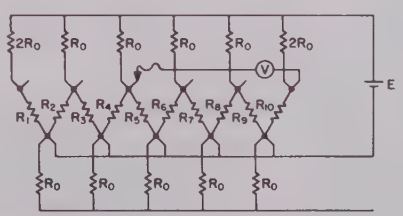
Find the maximum difference of values V for each bar

Use the greatest V difference to calculate $\left(\frac{r}{R}\right)_{MAX}$

for $r \ll R$ $\qquad \frac{V_{MAX} - V_{MIN}}{E} \approx \left(\frac{r}{R}\right)_{MAX}$

FIGURE 11. MEASURING THE SHORTING BAR RESISTANCE r

The value of $\frac{r}{R}$ can be found by measuring the voltage drops from a point on the bus bars to the junction of adjacent resistors, shown in Figure 11.



Connect the compensating network

Connect one shorting bar

Supply a voltage E from the shorting bar to the other side of the network

Measure the voltage V from one unused shorting bar terminal to each of the others

Change the shorting bar to the other side and repeat

Find the maximum voltage difference $\left(V_{MAX} - V_{MIN}\right)$ between terminals

Calculate $\left(\Delta_{R_0} - \Delta_R\right)_{MAX}$

$$\left(\frac{V_{MAX} - V_{MIN}}{E}\right)\left(2 + \frac{2R_0}{R} + \frac{R}{R_0}\right) = \left(\Delta_{R_0} - \Delta_R\right)_{MAX}$$

FIGURE 12. MEASURING THE 'BRIDGE UNBALANCE' $\left(\Delta_{R_0} - \Delta_R\right)$

The bridge unbalance can be measured as shown in Figure 12. The measured values of $\left(\frac{r}{R}\right)_{MAX}$ and $(\Delta_{R_0}-\Delta_R)_{MAX}$ can be multiplied together and doubled to give an upper bound of the connection error. This usually includes a very substantial safety factor. The same technique can be used in the series-parallel case.

MEASURING FOUR-TERMINAL BUILD-UP RESISTORS

The value for the parallel compensation resistors is a compromise. If they are too small the connection resistance will cause too much variation. If they are too large they will complicate the four-terminal measurement. For instance, if a Kelvin Bridge is used for the measurement, some of the parallel compensation resistors will be in series with the yoke of the bridge. If the yoke resistance is high relative to the measured resistance the measurement must be done carefully. There are at least two ways to reduce any problems that might arise. One method requires a more precise balance of the inner arms of the bridge, relative to the outer arms. Another method is to use a technique, such as interchange, which keeps the yoke resistance constant.

CONCLUSION

Consideration of the results shown above will show that it is possible to make four-terminal build-up resistor equipment that will permit the connection of 1Ω and higher valued resistors in series, parallel, or series-parallel with 1 ppm precision without the use of amalgamated mercury connections. The authors have assisted in the development of equipment of this type, some of which is shown in Figure 13. Figure 14 shows a practical junction design. All of the four-terminal resistances of these junctions are less than 0.5 microhms and can be made smaller if necessary. The measurement accuracy of this equipment can be predicted by additional measurements to show its connection accuracy.

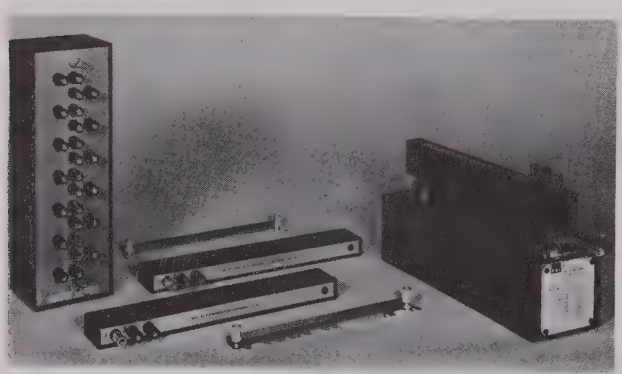


FIGURE 13. SOME FOUR-TERMINAL BUILD-UP RESISTOR EQUIPMENT

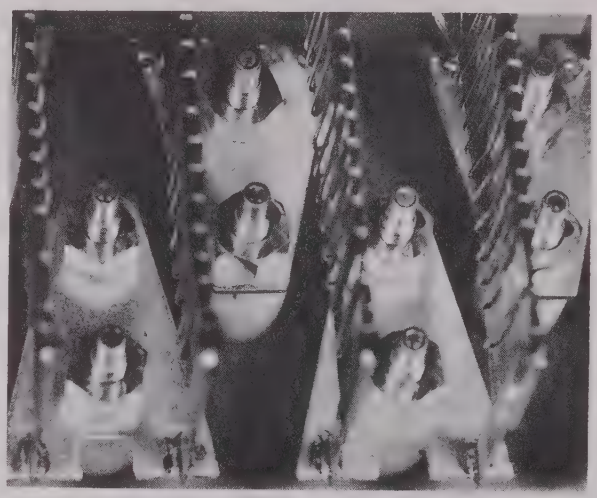


FIGURE 14. FOUR-TERMINAL JUNCTIONS

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c. Wenner, F. J., J. RES. NAT. BUR. STD., 25, p.229, (1940).

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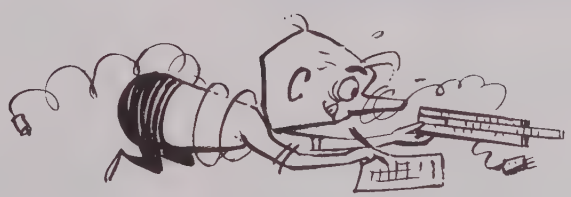
BRIDGES AND ACCESSORIES
no. 30
APRIL 1962

TRACEABILITY OF RESISTANCE MEASUREMENTS

BY
JACK C RILEY
DIRECTOR OF TECHNICAL SERVICES



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TRACEABILITY OF RESISTANCE MEASUREMENTS

A discussion of precision resistance comparison from certified standard to calibrated unit. The use of resistance transfer techniques is stressed. Four ter- resistance characteristics are discussed.

WHAT IS TRACEABILITY?

Air Force Bulletin NR. 520 which concerns calibration and certification of measuring and testing equipment (see Figure 1) calls for the use of

U.S. AIR FORCE
SPECIFICATION
BULLETIN

BULLETIN NR. 520
17 May 1960

CALIBRATION AND CERTIFICATION OF MEASURING AND TESTING EQUIPMENT

1. Scope and Purpose.

1.1. This bulletin applies when called out in a specification or other Air Force procurement document. It establishes requirements for calibration and certification of measuring and testing equipment used to assure specification conformance of supplies presented for Government acceptance.

FIGURE 1. SCOPE AND PURPOSE OF U.S. AIR FORCE SPECIFICATION BULLETIN NR. 520

"traceable" measurement standards, (see Figure 2). As a result of the call-

4. Traceability of Calibration.

4.1. In the Zone of Interior, Hawaii, and Alaska, measuring and testing equipment shall be calibrated with measurement standards, the calibration of which is traceable to the National Bureau of Standards, a Department of Commerce agency.

FIGURE 2. BEGINNING OF TRACEABILITY STATEMENT FROM USAF BULLETIN NR. 520

out of Air Force Bulletin NR. 520, more and more purchase orders are appearing with a request for traceability certification, (see Figure 3).

and 5.
put resistance 4K
inearity 0.005%
Part No. CA-999
"Certificate of Traceability is requested"

harge
ner E.S.

FIGURE 3. TYPICAL PURCHASE ORDER REQUEST

There is a good reason for this traceability requirement. Computer circuits, precision navigation equipment and other devices (see Figure 4) have increased the accuracy requirements for precision components. As a result, many industrial laboratories are now faced with making resistance calibration measurements and interlaboratory comparisons which only a few years ago were never attempted outside of national standards laboratories.

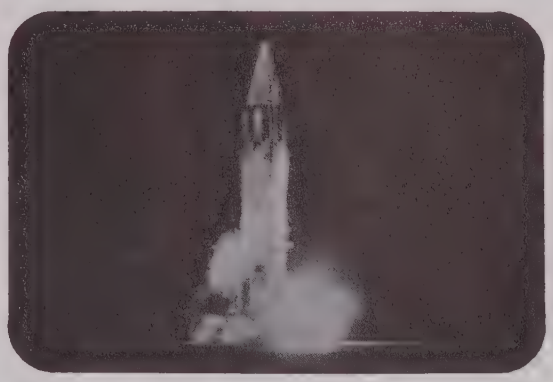


FIGURE 4. ONE REASON FOR PRECISION MEASUREMENTS

We are going to describe equipment and a technique for making resistance measurements of predictable accuracy relative to our national reference standards.

WHAT IS AN OHM?

Before we can get very far with a discussion of precision measurements, we need to reach an agreement as to what we mean by "one ohm". There are several meanings and at the one ppm level the resulting values can be different. We formerly used the "International Ohm", but we now use the

"Legal Absolute Ohm" which is the standard maintained by the National Bureau of Standards.

International Ohm

In 1894, the United States Congress defined the ohm as "the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice, 14.4521 grams in mass of a constant cross-sectional area, and of the length of 106.3 cm". This was the "International Ohm" and many of the older standard resistors were made using this unit. These resistors are about 0.05% high in terms of the present standard.

Absolute Ohm

Since July 21, 1950, the ohm in the United States has been defined as "--- one thousand million units of resistance of the centimeter-gram-second system of electromagnetic units---". This is the "absolute" ohm proposed by the International Committee on Weights and Measures.

Legal Absolute Ohm (NBS Standard)

Congress also determined that the legal value of the ohm "---shall be--- represented by, or derived from, national reference standards maintained by the Department of Commerce---". This means that the resistance standard maintained by the National Bureau of Standards is exactly correct, legally, although it may vary by a few ppm from the true value of the "absolute ohm". The standards of several countries are compared frequently and the NBS standard is in agreement with the resulting value determined by the International Bureau of Weights and Measures. When we have a resistor certified, the measured value on the certificate is in "legal absolute ohms" and the accuracy value refers only to measurement accuracy and expected stability for one year. No figure is given for the accuracy of the NBS standard in "absolute ohms". In most discussions, the NBS values are called "absolute ohms" because the standard at NBS is in agreement with the internationally accepted value of the absolute ohm.

A TRACEABLE MEASUREMENT

We propose that the following procedure and equipment will make measurements of predictable traceability, and it is therefore our opinion that the resulting calibrations should satisfy the traceability requirement.

We start out with a highly stable standard resistor which is measured at the National Bureau of Standards and returned to us with a certificate stating its measured value and expected stability. This reference standard establishes our unit of resistance, the ohm. To measure other resistors of the same value as our reference standard, we need an accurate comparison device. To measure resistors of different values from the standard we need a precision transfer technique.

THE CERTIFIED STANDARD RESISTOR

The standard resistor we are going to use for our measurements is a Thomas pattern one ohm resistor. These resistors, as shown in Figure 5, are commercially available and many of them are certified by the National Bureau of Standards to an accuracy of ±2 ppm per year. One such certificate is shown in Figure 6.

FIGURE 5. STANDARD RESISTOR

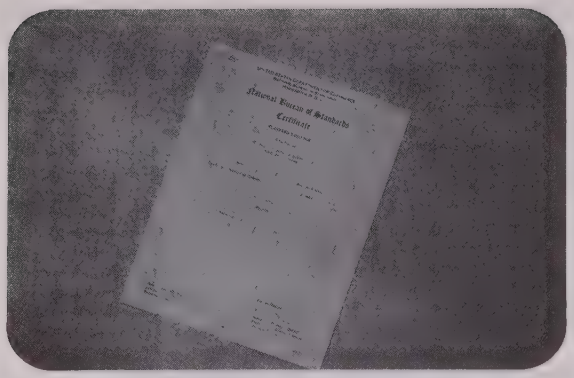


FIGURE 6. NBS CERTIFICATE

THE TRANSFER TECHNIQUE

The transfer system that we are going to discuss includes the ESI Model 242 Resistance Measuring System, used as a substitution type comparison bridge, a set of 3 ESI Model SR-1010 Transfer or Build-up Resistors and the associated shorting bars and compensation networks for calibrating resistors from one ohm to one megohm. This equipment is shown in Figure 7.

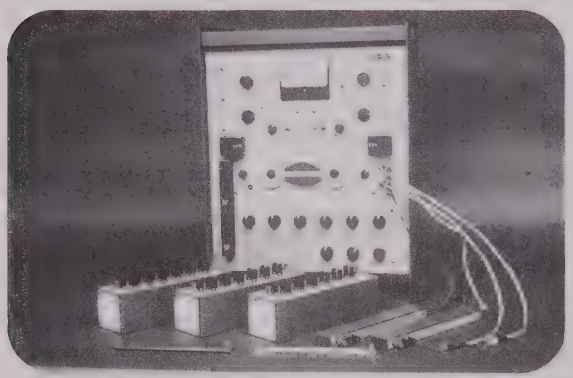


FIGURE 7. TRANSFER TECHNIQUE

HOW ARE RESISTORS CERTIFIED?

As a matter of interest let's go back to Washington DC and find out what happened when we submitted our standard resistor for certification, (see Figure 8).

FIGURE 8. NATIONAL BUREAU OF STANDARDS, ELECTRICITY DIVISION, WASHINGTON DC

ABSOLUTE MEASUREMENT OF RESISTANCE

The National Bureau of Standards is responsible for maintaining a prototype standard of resistance from which the legal unit of resistance for the United States is determined. It is possible to derive the unit of resistance from fundamental units of length, mass and time. One method of deriving the standard ohm involves the careful physical measurement of the standard inductor shown in Figures 9 and 10 and a set of careful electrical measurements to compare the inductor with the standard of resistance. The utmost precision and care are required for such

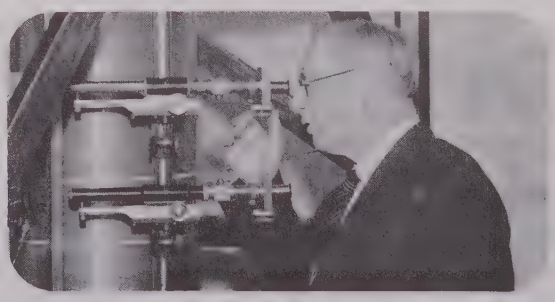


FIGURE 9. DR. FRANK WENNER MAKING PHYSICAL MEASUREMENTS OF THE STANDARD INDUCTOR (Photo Courtesy of NBS)

work. For example, the lamp post in Figures 10 and 11 contains the closest

piece of iron to the inductor when this experiment was performed.

FIGURE 10. ELECTRICAL MEASUREMENTS OF THE STANDARD INDUCTOR (Photo Courtesy of NBS)

FIGURE 11. PRESENT VIEW OF THE AREA SHOWN IN FIGURE 10

Very recently a computable capacitance standard has been devised which permits an alternate means for the derivation of the unit of resistance. This unit is shown in Figure 12.

Absolute Measurement of Resistance. An evaluation, based on the prototype standards of length and time, of the unit of resistance maintained at the Bureau was completed. The evaluation was based on a nominally 1-picofarad symmetrical cross capacitor having a value computable to high accuracy from its mechanical dimensions. The computable capacitor was used to establish the value of a 0.01-microfarad capacitor which then, through the medium of a frequency-dependent bridge, established the value of a 10,000-ohm resistor. A comparision of that resistor with the group of 1-ohm standard resistors currently used to maintain the NBS unit of resistance established the value of the unit with an estimated accuracy of the order of 2 ppm.

It is expected that an even higher accuracy will be attained in the repetition of these measurements. This method will greatly improve the Bureau's ability to check maintenance of the unit of electrical resistance through the use of a group of standard resistors. When combined with repetitions of determinations of the gyromagnetic ratio of the proton, the method can be used as a check of the stability of all types of electrical standards to a much greater accuracy than previously possible. *

*Electricity. Research Highlights of the National Bureau of Standards Annual Report, 1962, p. 3.

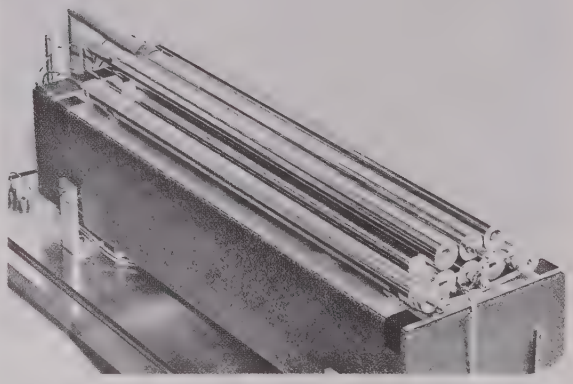


FIGURE 12. COMPUTABLE CAPACITANCE STANDARD (Photo Courtesy of NBS)

The fundamental unit of resistance for the United States is believed to be much more stable than one part per million per year. This standard is maintained by measurements on a group of precision one ohm resistors which have exhibited exceptional stability. These units are periodically checked by repeating the derivation experiment and they are also intercompared with the resistance standards of other nations. These resistors are in the back of the Wenner Bridge shown in Figure 13.

RESISTANCE COMPARISONS

Resistance comparisons of the highest accuracy are made using the Wenner resistance bridge shown in Figure 13. It can be used for comparing like values by substitution or interchange, or for making resistance ratio comparisons.

Ratio comparisons are made by using the seven-resistor build-up unit shown in Figure 14. This unit can be calibrated to provide precision ten to one and two to one ratios. Three 150 ohm resistors can be connected in parallel to give a value of 50 ohms. This resistance can be compared on a

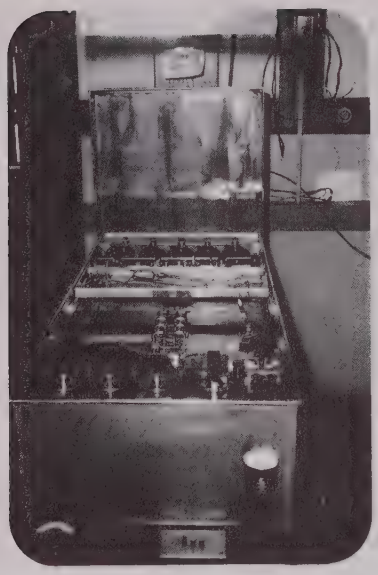
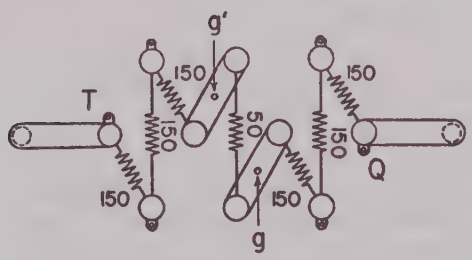


FIGURE 13. WENNER BRIDGE



Circuit diagram of the auxiliary apparatus used for determining the reading of the dial switches of the NBS precision bridge, for which the ratio of the resistance of the A arm to the resistance of the B arm is 10 to 1.

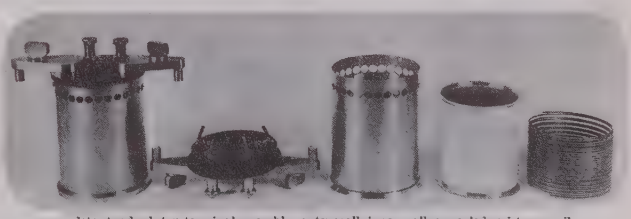
FIGURE 14. BUILD-UP CIRCUIT

one to one basis with the 50 ohm resistor and with the other set of three 150 ohm resistors also connected in parallel. Then the first three resistors can be reconnected in series and added to the 50 ohm resistor to make a total of 500 ohms. The series and parallel accuracies of the 150 ohm resistors are almost identical so that the true value of the ten to one ratio between the 500 ohm and 50 ohm resistance can be calculated to a predictable accuracy. A two to one ratio can be obtained by using two of the 50 ohm sections to make a 100 ohm resistor. The accuracy of the two to one ratio between this 100 ohm resistor and the remaining 50 ohms is also predictable. By a series of ratio measurements with this equipment it is possible to calibrate resistors of all reasonable values relative to the fundamental standard of resistance as maintained by the National Bureau of Standards. Certificates are issued relative to the value of the maintained standard of resistance (even though it may be a few ppm different from the "one thousand million units of resistance of the centimeter-gram-second system of electro magnetic units" which is the "absolute" ohm). The certificate which we receive includes the measured value of resistance and an indication of the expected stability of the resistor for at least a one year period (see Figure 15).

... and will be certified to an accuracy designed to indicate the degree of dependence which may ordinarily be placed on the standard for a period of one year. The certified accuracy will vary from 0.0002 percent to 0.01 percent depending on the nominal value of the standard, its type, age, and previous history. Well-aged standards in good condition having nominal values in the range 0.001 ohm to 10,000 ohms will usually be certified to 0.002 percent.

FIGURE 15. NBS CERTIFICATE VALUES
(Reprinted from "Federal Register", Vol. 26, No. 36, February 24, 1961.)

WHY THE THOMAS PATTERN ONE OHM



complete standard, top terminal assembly, outer wall, inner wall, annealed resistance coil.

(Photo Courtesy of NBS)

The Thomas pattern one ohm resistor is recommended as a reference standard because it is likely to have the best certified accuracy.

By alternate certification of several Thomas pattern one ohm units in a planned calibration program we can maintain a standard of resistance which we can trust to better than one part per million accuracy.

This is especially true if repeated calibrations show no significant changes.

HOW TO CALIBRATE RESISTORS

We need a measurement technique to transfer accuracies of this order from one ohm to other resistance values in our own laboratory.

Relative to the Thomas pattern one ohm standard, it is often possible to measure other resistors to a much greater accuracy than they are capable of being certified. Resistors with excellent short-term stability are often less stable over a long period of time or when subjected to environmental excursions or mechanical shock. A certificate must reflect this possible instability, but a recent calibration in an unchanging environment is much more trustworthy.

The ESI Model 242 Resistance Measuring System and Model SR-1010 Resistance Transfer Standards can be used for transfer measurement. The 242 Resistance Measuring System is used as a substitution type comparison bridge. The combination of both resistance measuring dials and a deviation dial in the Model 242 System makes it particularly well suited to this type of measurement. The SR-1010 units (Figures 16 and 17) make possible 100 to 1 resistance level transfers in a single step.

FIGURE 16. RESISTANCE TRANSFER STANDARD

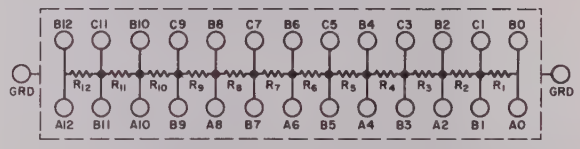


FIGURE 17. MODEL SR-1010 CIRCUIT DIAGRAM

The resistance transfer technique consists of connecting ten like resistors, first in parallel, Figure 18,

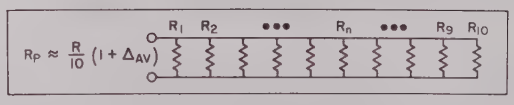


FIGURE 18. 10 RESISTORS IN PARALLEL

second in series to get a hundred to one resistance transfer, Figure 19,

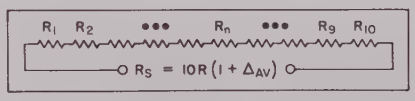


FIGURE 19. 10 RESISTORS IN SERIES

and third in a series-parallel combination of nine resistors which can be compared with either the series or parallel connection to give a ten to one difference, Figure 20.

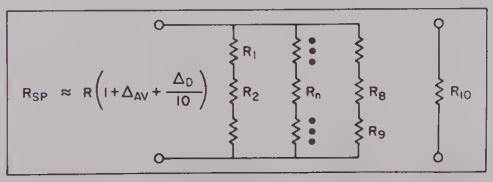


FIGURE 20. 10 RESISTORS WITH 9 IN SERIES-PARALLEL

We need to show how and why we can make transfer measurements which do not depend on the absolute accuracy of the transfer standard but only on its short term stability.

First we need some mathematical definitions so that we can derive our expected accuracy. We need a mathematical definition of resistance deviation in proportional parts which we will refer to as Δ. In Figure 21 we define

$$R_n = R(1+\Delta_n)$$

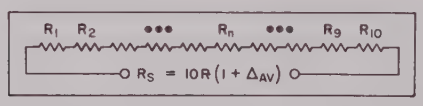
where
R_n – Resistance of nth resistor
R – Nominal resistance of each resistor
Δ_n – Deviation of R_n from R in proportional parts

FIGURE 21. WHAT Δ_n MEANS

the true resistance, R_n, of a resistor in terms of its nominal resistance R and its deviation Δ_n in proportional parts. If the resistor is close to its nominal value, Δ_n is a very small number.

SERIES RESISTANCE

We are going to use the first 10 resistors of the SR-1010 box. First, let us look at our ten resistors connected in series. The series resistance is the sum of the ten resistances. Each resistor value R_n can be stated in terms of its nominal resistance R and deviation Δ_n. The summation can be rearranged to give a resistance of 10 R with a deviation which is the average deviation of the ten resistors, as shown in Figure 22.



$$R_S = \sum_{n=1}^{10} R_n = \sum_{n=1}^{10} R(1+\Delta_n) = 10R\left(1+\frac{1}{10}\sum_{n=1}^{10}\Delta_n\right)$$

$$\Delta_{AV} = \frac{1}{10}\sum_{n=1}^{10}\Delta_n$$

where
Δ_{AV} – Average of the deviations Δ_n

$$R_S = 10R(1+\Delta_{AV})$$

FIGURE 22. SERIES CONNECTION--DEVIATION IS Δ_{AV}

PARALLEL RESISTANCE

The same ten resistors can be connected in parallel. The resulting resistance R_p deviates from R/10 by almost the average deviation of the ten resistors, as shown in Figure 23. If the ten resistors are enough alike, the

$$R_p = \frac{1}{\sum_{n=1}^{10}\frac{1}{R_n}}$$

where
R_p – Resistance of 10 resistors in parallel

$$\frac{1}{R_n} = \frac{1}{R(1+\Delta_n)} = \frac{1}{R}(1-\Delta_n+\Delta_n^2+\cdots)$$

$$R_p = \frac{1}{\sum_{n=1}^{10}\frac{1}{R}(1-\Delta_n+\Delta_n^2+\cdots)} = \frac{R}{10}\left[\frac{1}{1+\frac{1}{10}\sum_{n=1}^{10}(-\Delta_n+\Delta_n^2+\cdots)}\right]$$

$$R_p = \frac{R}{10}\left[1+\frac{1}{10}\sum_{n=1}^{10}\Delta_n-\frac{1}{10}\sum_{n=1}^{10}\Delta_n^2+\left(\frac{1}{10}\sum_{n=1}^{10}\Delta_n\right)^2+\cdots\right]$$

$$R_p \approx \frac{R}{10}(1+\Delta_{AV})$$

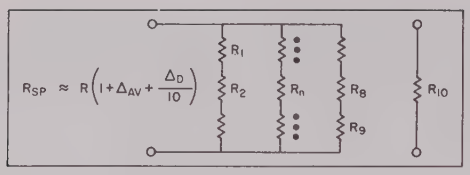
FIGURE 23. PARALLEL CONNECTION--DEVIATION IS ALSO Δ_{AV}

"almost" is insignificant. The error which arises from assuming that the series and parallel connections have the same deviation from their nominal values is in the order of the square of the average deviation $(\Delta_{AV})^2$ of the ten resistors from their nominal value. If Δ_n is less than 100 ppm then $(\Delta_{AV})^2$ will be less than 0.01 ppm. The Δ_n of resistors of the ESI Model SR-1010 is typically less than 20 ppm so for 1 ppm measurements, the assumption that $(\Delta_{AV})^2$ terms can be dropped is quite valid.

Because the same ten resistors with the same Δ_{AV} are used for the series and parallel connections, we can measure Δ_{AV} by comparison to a standard of either R/10 or 10R and reconnect the SR-1010 to provide a standard of the same accuracy at the other value, 10R or R/10, one hundred times removed.

SERIES-PARALLEL RESISTANCE

By one additional measurement we can calibrate nine of our ten resistors for use as a standard of similar accuracy for ten to one transfers.



$$R_{SP} = R\left[1+\Delta_{AV}+\frac{\Delta_D}{10}+\begin{Bmatrix}+0\\-(\Delta_{MAX})^2\end{Bmatrix}+\cdots\right]$$

where
- R_{SP} – Resistance of 9 of 10 resistors R_i connected in Series-Parallel
- Δ_D – Deviation of R_{SP} from the tenth resistor R_{10} $[R_{SP} \equiv R_{10}(1+\Delta_D)]$
- Δ_{MAX} – Magnitude of largest deviation Δ_n

$$R_{SP} \approx R\left(1+\Delta_{AV}+\frac{\Delta_D}{10}\right)$$

FIGURE 24. SERIES-PARALLEL CONNECTION - - DEVIATION IS

$$\Delta_{SP} = \Delta_{AV} + \frac{\Delta_D}{10}$$

In Figure 24 we have connected the first nine resistors R_n in three parallel strings of three resistors in series. The resulting resistance R_{SP} is nominally the same as each resistor R. The deviation Δ_{SP} of this series-parallel combination is almost exactly the average deviation of the nine resistors, because each resistor's contribution to the deviation is approximately the same in either series or parallel. If we knew Δ_{SP} and the deviation Δ_{10} of the tenth resistor we could easily combine them to find the average deviation of all ten resistors which we already know as Δ_{AV}. We could also find Δ_D, which is defined as the deviation of the series-parallel nine resistors R_{SP} from the tenth resistor R_{10}. Actually if we know any two of these four variables, Δ_{AV}, Δ_{SP}, Δ_D and Δ_{10} we can find the other two.

It is easy to measure Δ_D by comparing R_{SP} with R_{10}. We can measure Δ_{AV} or Δ_{SP} relative to a standard of any one of the three decade values R/10, R, or 10R. From the two measured values we can calculate the other one, Δ_{SP} or Δ_{AV}. Thus we can calibrate the SR-1010 box at any one of the three resistance levels and use it as a calibrated standard at the other two.

We can also use R_{SP} for standardizing the bridge to calibrate each individual resistor in the SR-1010 box. Then resistance values are available in integer steps from one R to twelve R with known accuracy.

LEAD AND CONTACT RESISTANCE

We are starting a chain of measurements with a one ohm standard resistor. One part per million of one ohm is one microhm. One microhm is less than the resistance of a 0.010 inch length of number twelve copper wire. Also, each lead of the Thomas pattern one ohm standard has a resistance of about one milliohm. Lead and contact resistances are a very serious problem. Fortunately the effects of lead and contact resistance can be minimized by using four-terminal resistance connections and a Kelvin ratio bridge, such as the ESI Model 240.

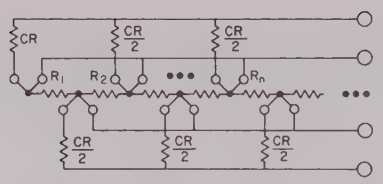
FOUR-TERMINAL SERIES MEASUREMENTS

The ESI Model SR-1010 Transfer Resistance Standard consists of twelve nominally equal resistors permanently connected in series with two terminals brought out from each resistor junction. This allows a four-terminal measurement of any individual resistor and of any series combination of adjacent resistors (See Figure 17).

FOUR-TERMINAL PARALLEL MEASUREMENTS

Fortunately four-terminal parallel connections can also be made. A special compensation network, using additional matched resistors in series with one of the leads on each end of the resistors, allows us to make accurate parallel measurements of low valued resistors.

The circuit for four-terminal parallel measurements is shown in Figure 25. The connection circuit contributes a measurement uncertainty Δ_M. The first order approximation for Δ_M in



$\Delta_M = 2M\Delta$

where M – Ratio of low connection resistance to resistance being paralleled
Δ – Unbalance of high connection resistances in proportional parts

FIGURE 25. FOUR-TERMINAL PARALLEL CONNECTION

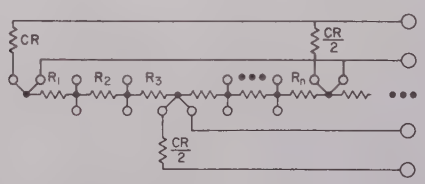
proportional parts is $2M\Delta$. M is the ratio of the highest shorting bar resistance to the resistance R_n of the resistors being paralleled. Δ is the relative unbalance of the compensating resistors CR. If we are paralleling 10 ohm resistors with 10 milliohm buss bars and are using compensating resistors which are matched to 0.1%, we will have a four-terminal resistor which is within 1 ppm of the parallel resistance of the resistors being paralleled,

$$R_p = (1 \text{ ohm})\,(1 + \Delta_{AV}) \pm 1 \text{ ppm.}$$

In the SR-1010 we have both lower shorting bar resistance and better matched compensating resistors, so we get much better than 1 ppm calibration accuracy at one ohm and even greater accuracy for higher resistances.

FOUR-TERMINAL SERIES-PARALLEL MEASUREMENTS

The series-parallel connection of nine low-valued resistors can be done with another compensating network and a different connection of the shorting bars (see Figure 26). We are in effect paralleling three resistors, so the same connection technique is used and the same accuracy is obtained as with the parallel connection.



$\Delta_M = 2M\Delta$

where M – Ratio of low connection resistance to resistance being paralleled
Δ – Unbalance of high connection resistances in proportional parts

FIGURE 26. FOUR-TERMINAL SERIES-PARALLEL CONNECTION

FOUR-TERMINAL JUNCTIONS

The resistors in the SR-1010 box must be connected by true four-terminal "point" junctions, with two leads going to the resistors and two to the terminals. Some physical shapes which give four-terminal junctions are shown in Figure 27. The test for a four-terminal point junction is also shown. The meter voltages divided by the generator currents represent the possible resistance measurement error. For the junctions in the SR-1010 box, shown in Figure 28. These resistances are typically less than 0.1 microhm causing much less than one ppm deviation for even a one ohm per step box.

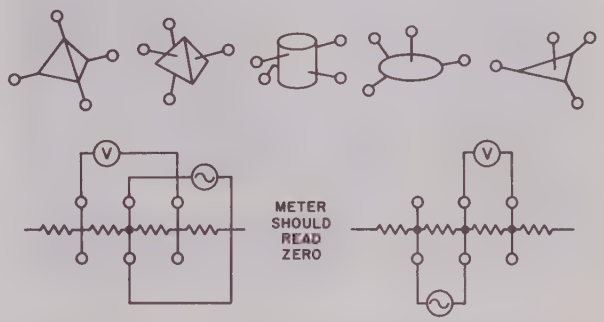


FIGURE 27. FOUR-TERMINAL JUNCTIONS

FIGURE 28. SR-1010 BOX JUNCTIONS

LET'S MAKE SOME TRACEABLE MEASUREMENTS

Our one ohm reference standard was sent to the National Bureau of Standards for certification, and we want to use it to calibrate our working standards of other values. We connect

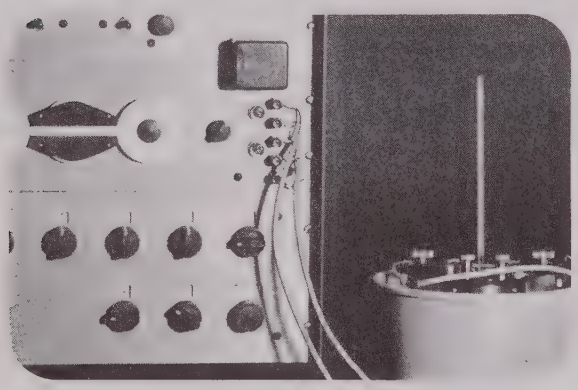


FIGURE 29. CONNECTING THE REFERENCE STANDARD

the reference standard to the bridge (Figure 29) and set the bridge deviation dial to the certified deviation of the standard (Figure 30).

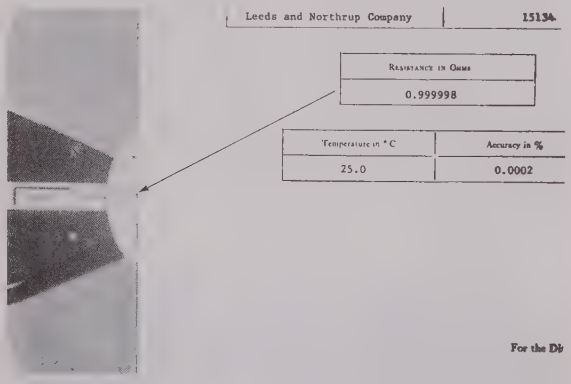


FIGURE 30. CERTIFIED DEVIATION

Caution: The standard resistor has a fairly high temperature coefficient and a long thermal time constant so it must be kept at the same known temperature for a long time before measurement. The resistance-temperature plots for three Thomas type one ohm resistors are shown in Figure 31.

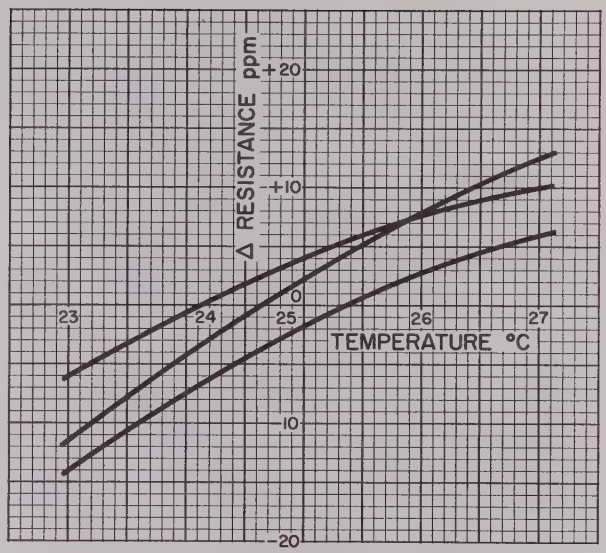


FIGURE 31. RESISTANCE TEMPERATURE CURVES

The bridge and transfer resistors do not reqire precision temperature control or monitoring for two reasons. First, they depend on short-term stability, not absolute accuracy. Second, the 100 ohm and higher bridge and transfer resistors are made of Evanohm wire so they can withstand small temperature variations with much less degradation than their Manganin counterparts. Typical temperature response curves for Evanohm and Manganin are shown in Figure 32.

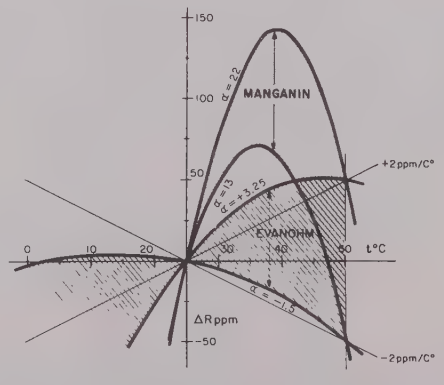


FIGURE 32. TEMPERATURE RESPONSE CURVES

Having set the bridge deviation dial to the certified deviation of the reference standard from its nominal value, we balance the bridge by means of the resistance dials. We ignore their readings; this adjustment calibrates the bridge for direct readings on the deviation dial of deviation from one ohm in parts per million.

We can now replace the one ohm reference standard by ten parallel-connected 10 ohm resistors in an SR-1010 box, rebalance the bridge by the deviation dial (Figure 33) and read directly Δ_{AV}, the average deviation

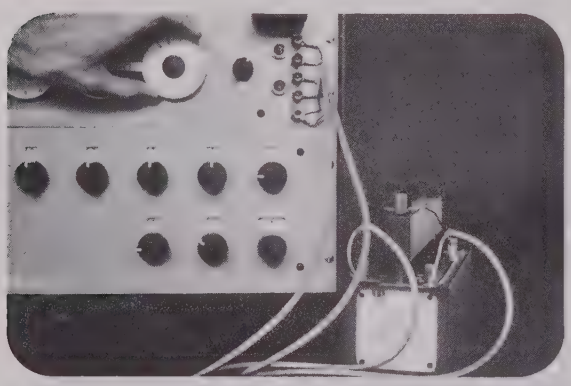


FIGURE 33. MEASURING Δ_{AV}

of the ten resistors from the nominal value of the reference standard.

To calibrate the bridge at 100 ohms, we will reconnect the box to use the

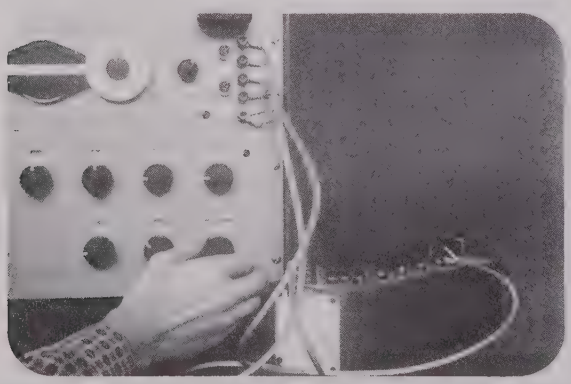


FIGURE 34. CALIBRATION OF THE BRIDGE TO READ 100 OHMS

same ten resistors in series (Figure 34). We leave the measured value of Δ_{AV} set on the deviation dial and balance the bridge at 100 ohms by means of the resistance dials (again ignoring their readings). The bridge is calibrated for direct readings of the deviation of 100 ohm resistors from 100 times the nominal value of the reference standard as shown in Figure 35.

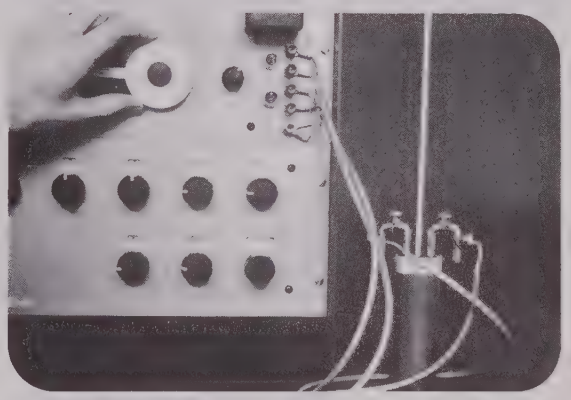


FIGURE 35. MEASURING A 100 OHM RESISTOR

With this bridge calibration, the Δ_{AV} of ten 1 kilohm resistors connected in parallel can be measured. The 1 kilohm resistors can be connected in series to calibrate the bridge deviation readings at 10 kilohms. The same procedure can be repeated with ten 100 kilohm resistors to calibrate the bridge for reading 1 megohm. Note that the transfer of calibration from one ohm to one megohm has been made in only three steps, minimizing the problem of error accumulation in a long series of measurements.

To calibrate the bridge for intermediate values, we must intercompare the resistors in an SR-1010 box. In the ten ohm per step box, for example, we will start by measuring the difference of the series-parallel connected group of nine resistors from the tenth resistor. In Figure 36, we connect the tenth resistor R_{10} to the bridge, set the deviation dial to zero and balance the bridge using the resistance dials.

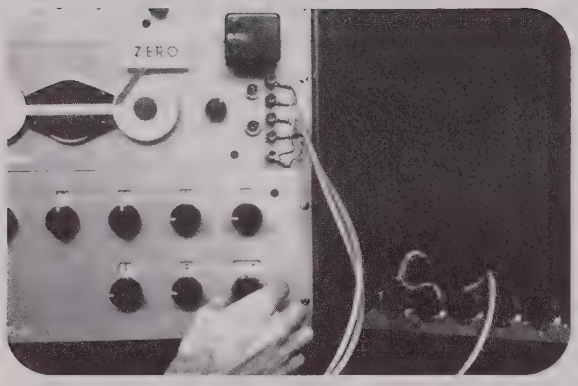


FIGURE 36. CALIBRATION OF THE BRIDGE TO READ Δ_D

We now connect the series-parallel group to the bridge, rebalance by means of the deviation dial to read Δ_D (Figure

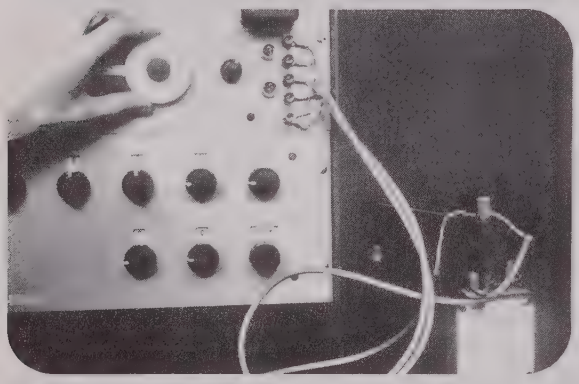


FIGURE 37. READING Δ_D

37) and calculate $\Delta_{SP} = \Delta_{AV} + (\Delta_D/10)$. ($\Delta_D$ can be measured to the same accuracy as Δ_{AV} so $\Delta_D/10$ is ten times as accurate as Δ_{AV} therefore Δ_{SP} will have essentially the same accuracy as Δ_{AV}). Leaving the series-parallel circuit connected to the bridge, we set the deviation dial to Δ_{SP} and rebalance the bridge by the resistance dials (Figure 38). The bridge is now standardized to measure the deviation of any other ten ohm resistors as shown in Figure 39.

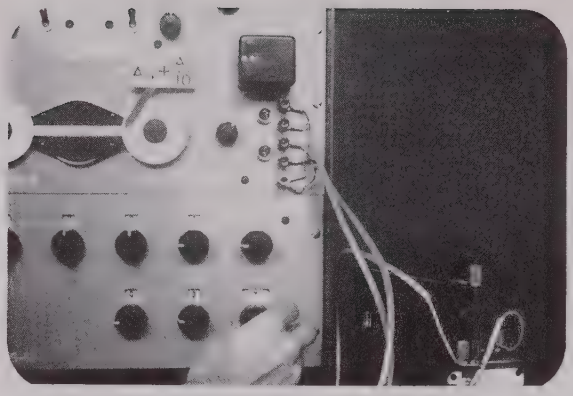


FIGURE 38. CALIBRATION OF THE BRIDGE TO READ 10 OHMS

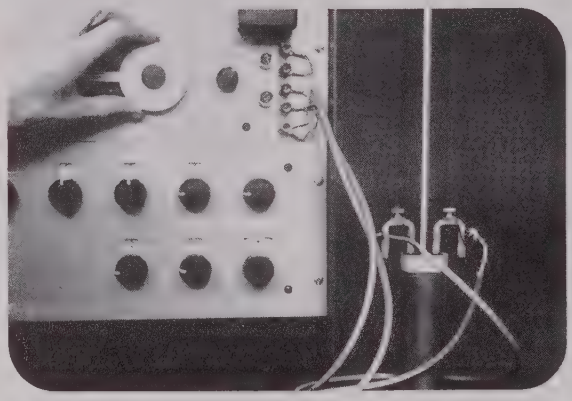


FIGURE 39. MEASURING 10 OHMS

This adjustment can also be used to measure the deviation of each of the individual resistors in the SR-1010 for use at any multiple of 10 ohms up to 120 ohms. This type of calibration of the various SR-1010 boxes can be used to calibrate each step of the decade resistance dials of the bridge. In measuring unusual resistance values, it is often sufficient to standardize the bridge at the first sginificant figure, using the deviation as a bridge calibration adjustment to make the bridge read correctly at that step on that decade. Nearby resistance values can then be read directly with good accuracy, since errors in the less significant figures will contribute much less measurement error.

SYSTEM ACCURACY

With the equipment described, a careful operator in an air conditioned laboratory can consistently compare two like resistance values in the range from an ohm to above a megohm to an accuracy of 2 ppm, except at the one ohm ohm level, where detector sensitivity may limit the accuracy to about 4 ppm. Using these figures and assuming a Thomas pattern reference standard certified to 2 ppm as the starting point, the system accuracy table shown in Figure 40 can be constructed. Note

			RESISTANCE VALUE	CALIBRATION ACCURACY OF STANDARD	ACCURACY OF CALIBRATED BRIDGE
LEGAL STANDARD AT NBS			1 Ω	0 ppm	———
LABORATORY REFERENCE STANDARD			1 Ω	2 ppm	6 ppm
esi MODEL SR-1010 TRANSFER STANDARDS CALIBRATED AT TIME OF USE	10Ω/STEP	PARALLEL	1 Ω	6 ppm	———
		SERIES-PARALLEL	10 Ω	6 ppm	8 ppm
		SERIES	100 Ω	6 ppm	8 ppm
	1k/STEP	PARALLEL	100 Ω	8 ppm	———
		SERIES-PARALLEL	1 k	8 ppm	10 ppm
		SERIES	10 k	8 ppm	10 ppm
	100k/STEP	PARALLEL	10 k	10 ppm	———
		SERIES-PARALLEL	100 k	10 ppm	12 ppm
		SERIES	1 MEG	10 ppm	12 ppm

FIGURE 40. TRANSFER ACCURACY

that the accuracy obtained is substantially better than present certification at all levels above one ohm. At the one megohm level, for example, the transfer standard is known to 10 ppm and any other stable one megohm resistor can be measured to 12 ppm. Where the ultimate accuracy of the system is desired, the calibration procedure should be made a routine part of the operating procedure. By using extra care and multiple readings in making a measurement the accuracy can be improved even further. At these levels of accuracy, statistical analysis of repeated measurements should be made to determine the accuracy corresponding to any specified probability or confidence factor.

Since the calibration procedure is so rapid (three substitution type comparisons to determine Δ_{AV} for all three boxes) it is easy to accumulate enough calibration history in a short time to indicate how frequently the procedure should be repeated for any particular set of ambient conditions and desired accuracies. In many air conditioned laboratories, measurements will be found to repeat consistently over a period of many weeks or even months to a closer tolerance than that listed in Figure 40. Where these limits of error are sufficient, the boxes can then be used as working standards with accuracies in air approaching those of NBS pattern resistors in an oil bath.

MORE ABOUT RESISTANCE MEASUREMENT

(1) Precision Resistance Measurement-Part I. ESI Design Ideas, Vol. 1, No. 2, July 1960.

(2) Precision Resistance Measurement-Part II. ESI Design Ideas, Vol. 1, No. 3, November 1960.

(3) A 1-100Ω Build-up Resistor for the Calibration of Standard Resistors, B. V. Hammon. Journal of Scientific Instruments, Vol. 31, No. 12, Dec. 1954.

(4) Establishment and Maintanence of the Electrical Units, F. B. Silsbee. NBS Circular 475, June 30, 1949. Reprinted in Precision Measurement and Calibration, Vol. 1, Feb. 1961

(5) Precision Resistors and their Measurement, James L. Thomas. NBS Circular 470, Oct. 8, 1948. Reprinted in Precision Measurement and Calibration, Vol. 1, Feb. 1961.

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